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Flying Training

WEATHER FOR AIRCREWS

To familiarize the aircrew member with fundamentals of weather. It serves as a text for the undergraduate pilot and navigator training programs, all USAF instrument refresher training and flight instruction programs, and various individual flying training programs. It is issued to each flying unit and to each instructor and student involved in such training.

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CHAPTER 1

THE EARTH'S ATMOSPHERE

The earth has two basic motions within the solar system with relation to the sun (figure 1-1). The first is the daily rotation of the earth about its axis. A complete rotation of the earth about its axis takes about 24 hours so that each hour represents 15 degrees rotation (1,030.62 miles at the equator). This rotation causes periods of daylight and darkness which, in turn, produce numerous weather effects and cause a predictable effect on the flow of wind on the surface of the earth, as we shall see in Chapter 5.

The other basic motion is its slightly elliptical orbit about the sun which is completed each 365¼ days. The plane of the earth's orbit around the sun is called the plane of the ecliptic. Since the earth's axis is tilted about 23½° from the vertical to the plane of the ecliptic, we experience the seasons of summer, fall, winter, and spring.

The tilt of the axis accounts for the great seasonal variations in weather that occur in the middle and high latitudes. Refer to figure 1-1 and note that when the earth is at position A in its orbit, the North Pole tilts toward the sun. The Northern Hemisphere is then experiencing summer because it is receiving the most solar energy (insolation). When the South Pole tilts toward the sun (position B), the Southern Hemisphere is having summer. Spring and fall begin when the earth has moved to a respective location in its orbit which results in nighttime and daylight hours of equal length anywhere on earth (positions C and D). These positions in the earth's orbit are called equinoxes and occur on or about March 21 and September 22.

In addition, numerous local changes in weather patterns are influenced by the shape and composition of the earth itself as we shall see in subsequent chapters.

STRUCTURE AND COMPOSITION

The Atmosphere

The atmosphere is the gaseous envelope covering the earth and held in place by gravity. If the earth were compared to a baseball, the atmosphere, in perspective, would be about as thick as the baseball's cover. This envelope of air rotates with the earth. The atmosphere also has a motion relative to the earth's surface; a continuous motion called circulation. Although other factors influence circulation, it is created primarily by the large difference between temperatures over the tropics and those over the polar regions. Circulation is also influenced by uneven heating of land and water areas by the sun.

The atmosphere consists of a mixture of various gases. Pure, dry air is composed of about 78 percent nitrogen, 21 percent oxygen, and a 1 percent mixture of other gases, mostly argon (figure 1-2).

Suspended in the air is water vapor, which varies in amounts from 0 to 5 percent by volume. The maximum amount of water vapor the air can hold depends primarily on the temperature of the air; the higher the temperature, the more vapor it can hold. The water vapor will remain suspended in air until, through condensation, it grows to sufficient droplet or ice crystal size to fall to the earth as precipitation.

Even when the atmosphere is apparently clear, it contains variable amounts of impurities, such as dust and salt particles. When these impurities are relatively numerous, they cause haze and reduce visibility.

The depth of the atmosphere is as much as 300,000 feet at points (figure 1-3). Roughly half of it, by weight, lies below 18,000 feet because of the gravitational pull of the earth. This creates a blanket of dense air at the earth's surface upon which other forces act, as we will see in subsequent chapters.

The atmosphere is divided into layers, or spheres, each having certain properties and characteristics. Since most weather occurs in the troposphere and since most flying is in the troposphere and stratosphere, we will restrict our discussions to these two layers.

Troposphere

The troposphere is the layer adjacent to the earth. It varies in depth from an average of 60,000 feet over the equator to 28,000 feet over the poles, with greater depth in summer than in winter. It is characterized by a decrease in temperature with height (figure 1-4).

The top of the troposphere is the *tropopause* which serves as the boundary between the troposphere and the stratosphere. The location of the tropopause is usually characterized by a pronounced rate of temperature change with altitude.

The tropopause acts like a "lid" in that it resists the exchange of air between the troposphere and the atmosphere above. This explains why almost all water vapor is found in the troposphere. Above the tropopause are the stratosphere, the mesosphere, and the thermosphere (figure 1-3). We will only discuss the stratosphere as an influence on weather above the troposphere.

Stratosphere

The atmospheric layer just above the tropopause is the stratosphere. The average altitude of the top of this layer is 22 miles. Characteristics of this layer are a slight *increase* in temperature with height (as opposed to the *decrease* encountered in the troposphere) and the near absence of water vapor and clouds. Occasionally a strong thunderstorm will break through the tropopause, and in very rare instances an aggregate of ice crystals will form the *mother of pearl cloud*.

Except for a substantial increase in the amount of ozone, the composition of the stratosphere is the same

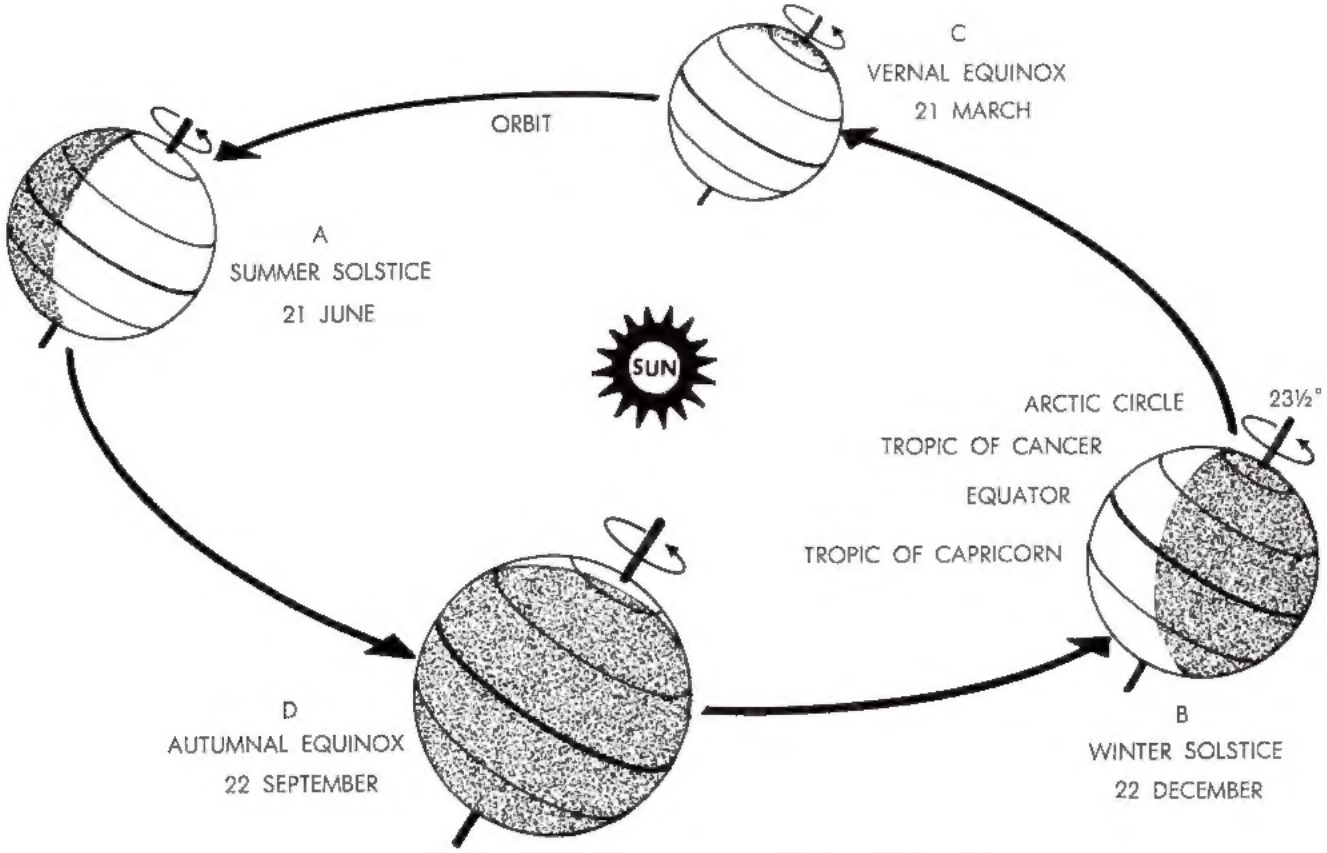


Figure 1-1. Earth's Rotation, Axis Tilt, And Orbit.

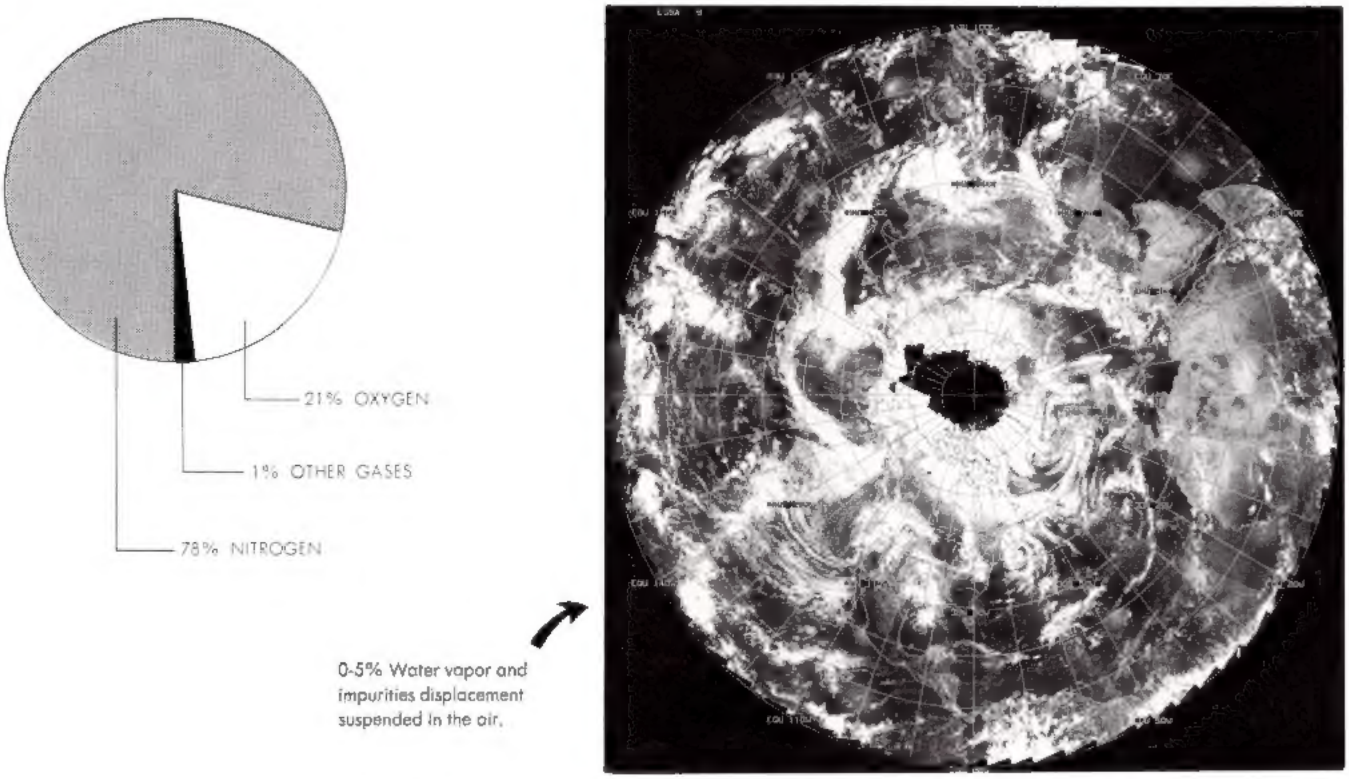


Figure 1-2. Composition of Atmosphere.

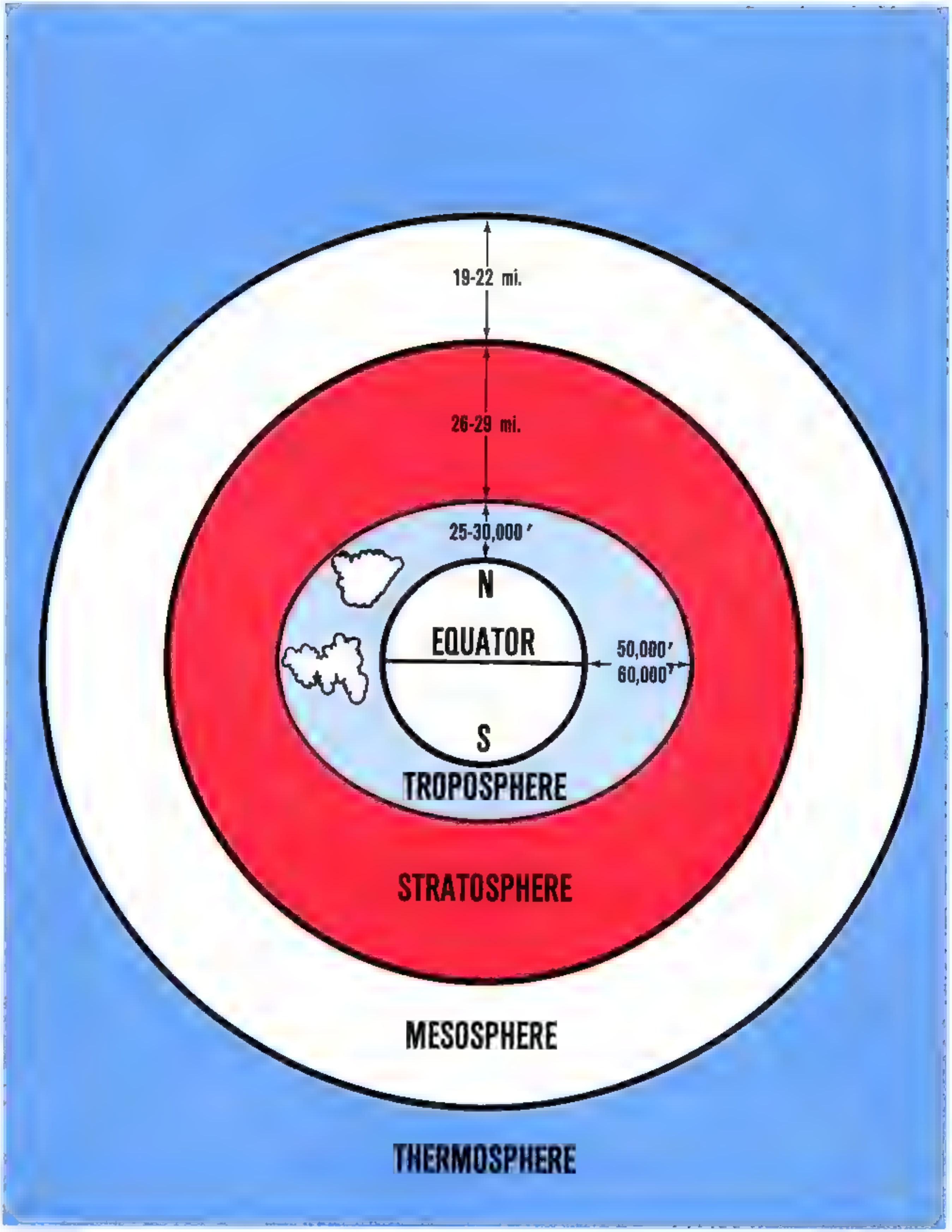


Figure 1-3. Atmospheric Layers.

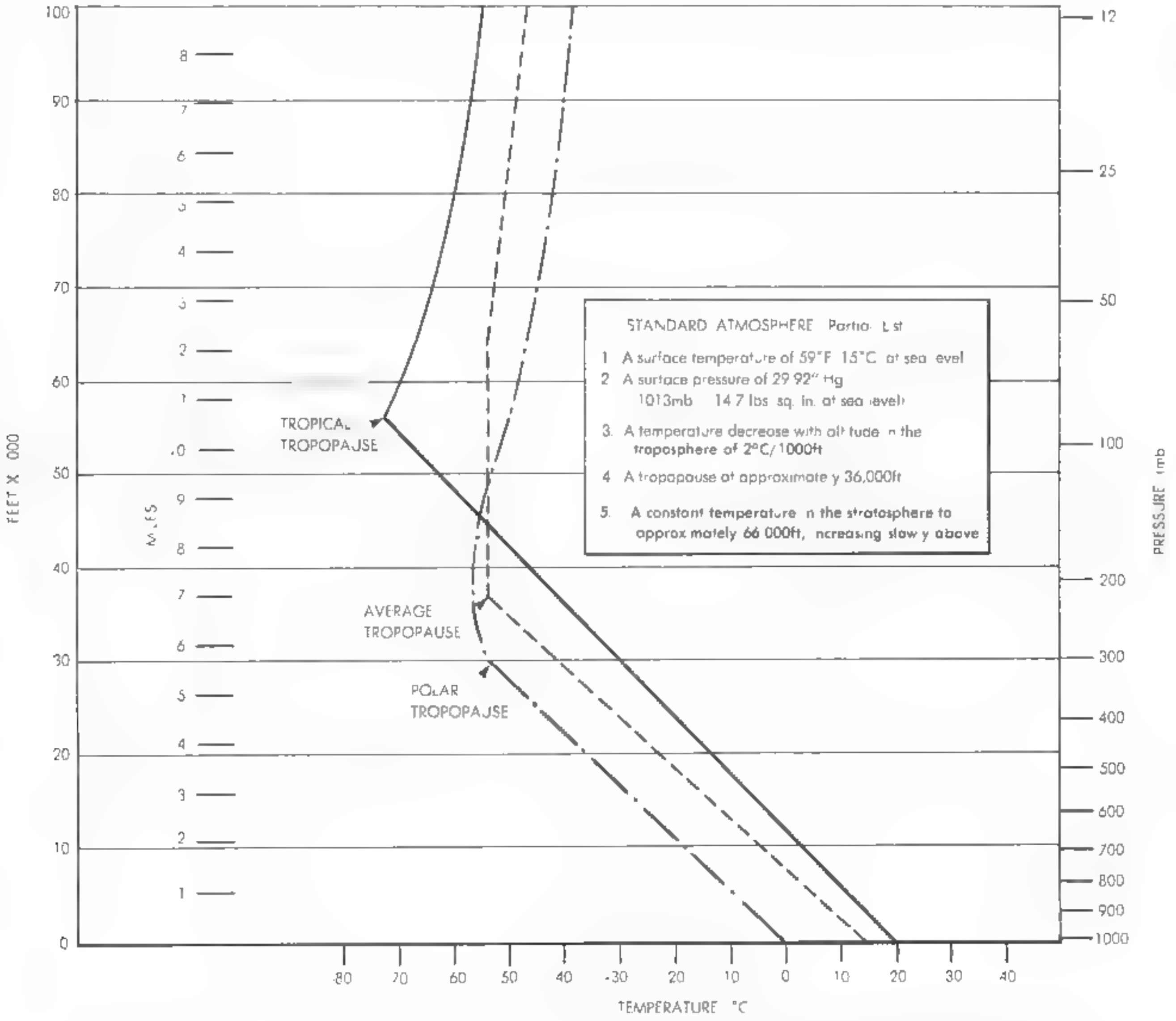


Figure 1-4. Troposphere Characterized By Decrease In Temperature With Height.

as that of the troposphere. Ozone is important because it absorbs most of the deadly ultraviolet rays from the sun. Ozone also has a corrosive effect on certain metals and has become increasingly important as supersonic aircraft operate in the regions of higher ozone concentration. Aircrews flying through areas of higher ozone concentration may experience irritation to eyes, nose, and mouth, or coughing symptoms associated with ozone sickness

AIRCREW ENVIRONMENT

Because the atmosphere contains 21 percent oxygen, the pressure oxygen exerts is about one-fifth of the total air pressure at any one given level. This is important to aircrews because the rate at which the lungs absorb oxygen depends upon the oxygen pressure. The average person is accustomed to absorbing oxygen at a pressure of about 3 pounds per square inch. Since air pressure decreases with increasing altitude, oxygen pressure also decreases. Prolonged high altitude flight without supplemental oxygen will usually produce a feeling of exhaustion, then an impairment of vision, and finally unconsciousness - symptoms of hypoxia. Since the first effects can occur without the person realizing it, auxiliary oxygen should be used during prolonged flights above 10,000 feet, or when flying above 12,000 feet for even short periods of time. When the atmospheric pressure falls below 3 pounds per square inch (approximately 40,000 feet), a system of environmental pressurization becomes essential.

CHAPTER 2

MOISTURE

More than two-thirds of the earth's surface is covered with water. Water from this extensive source is continually evaporating into the atmosphere, cooling by various processes, condensing, and then falling to the earth again as precipitation. This never-ending process is referred to as the hydrologic cycle (figure 2-1). This cycle keeps the atmosphere supplied with moisture and aids in producing temperature and pressure changes (figure 2-2)

The remaining third of the earth's surface is composed of land of various and vastly different terrain features. We shall see later that knowledge of terrain differences is very important in weather forecasting. Terrain varies from large-scale mountain ranges and deserts to minor rolling hills and valleys. Each type of terrain significantly influences local wind flow, moisture availability, and, in turn, the resulting weather.

Water in the atmosphere is found in three states. vapor, liquid, and solid. Water vapor is water in the gaseous state and is not visible. As a liquid, it is found as rain, drizzle, and as the small water droplets which form clouds and fog. As a solid, it takes the form of snow, hail, ice pellets, ice-crystal clouds, and ice-crystal fog.

Water vapor is the most important single element in the production of clouds and other visible weather phenomena. However, it can create problems or hazards for the flyer when it changes into the liquid or solid state.

Most of the atmosphere's moisture is concentrated in the lower troposphere, and only rarely is it found in significant amounts above the tropopause.

The oceans are the primary source of water for the atmosphere, but it is also furnished by lakes, rivers, swamps, moist soil, snow, ice fields, and vegetation. Moisture is introduced into the atmosphere in its vapor state, and may then be carried great distances by the wind before it eventually falls as liquid or solid precipitation.

CHANGES OF STATE

Evaporation, condensation, sublimation, freezing, and melting are changes of state. In the change of water from a liquid to a gas, molecules escape from the surface of the liquid and enter the air as water vapor The rate of their escape increases as the temperature at the liquid's surface increases This is a simplified explanation of *evaporation*, the process through which water vapor enters the atmosphere from liquid water. *Condensation* is the reverse process. *Sublimation* is the changing of ice directly to water vapor, or water vapor to ice, bypassing the liquid state in each process. *Freezing and melting* processes are familiar to each crew member.

Any change of state involves heat exchange. That is, heat energy is used or released. Figure 2-3 illustrates the heat exchanges between the different states of water. During evaporation, escaping water molecules use energy (heat) to break away from the attraction of the other molecules. The remaining liquid is cooled since it has less heat. The heat required for the evaporation process is not lost, but remains hidden or latent in the water vapor. When the vapor condenses to liquid water or sublimates directly to ice, this heat is released to the atmosphere as illustrated in figure 2-4, and the surrounding air becomes warmer. As an example, the

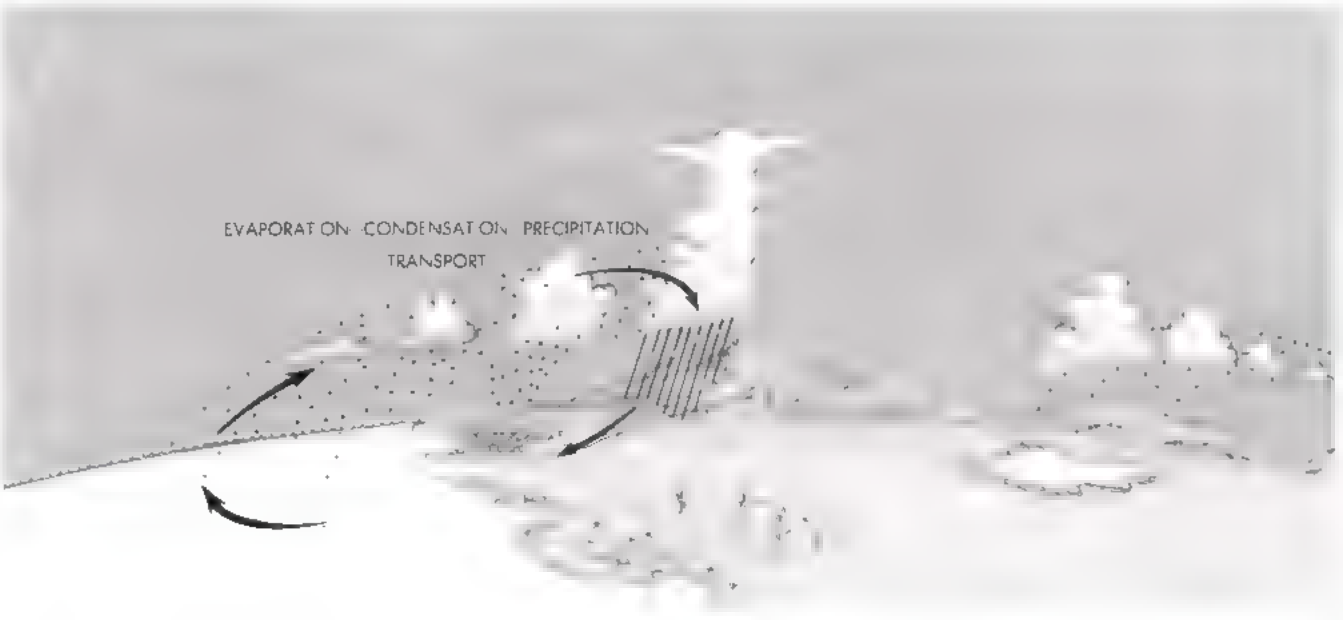


Figure 2-1. Hydrologic Cycle.

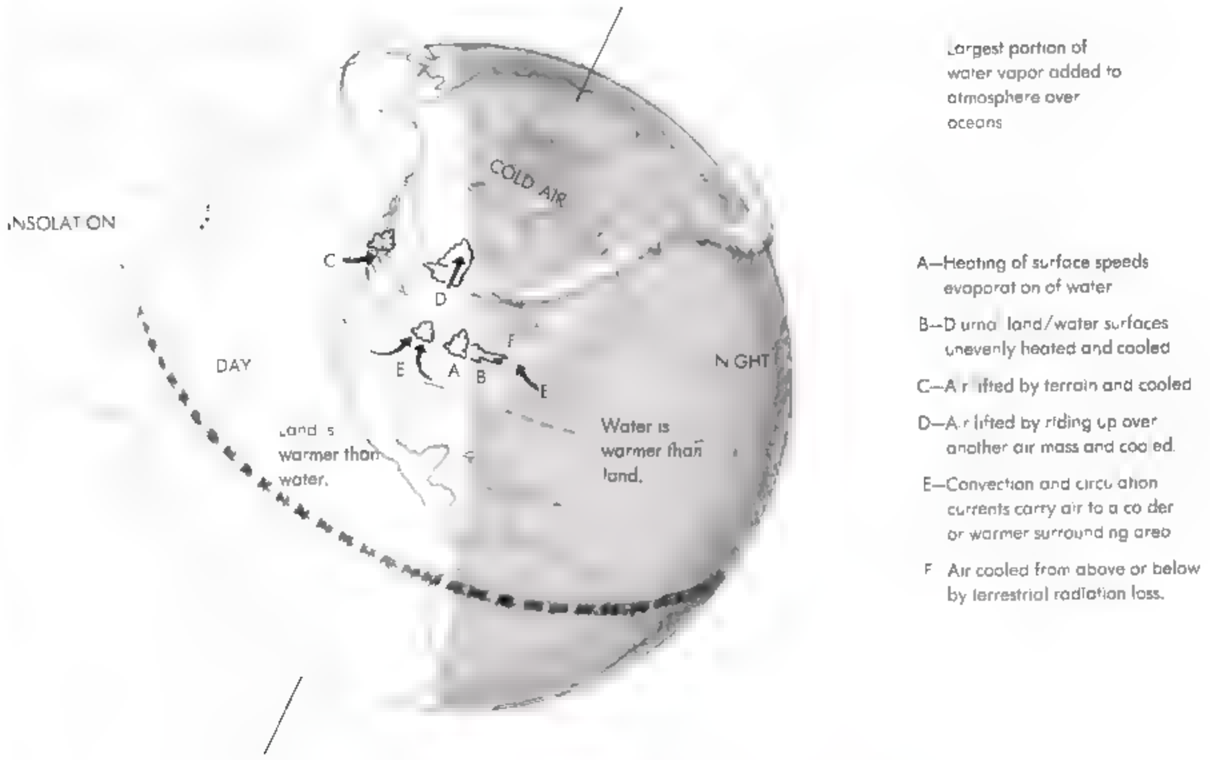

Largest portion of water vapor added to atmosphere over oceans
COLD AIR
INSOLATION
C
D
DAY
E
A
B
F
E
NIGHT
Land is warmer than water.
Water is warmer than land.
A—Heating of surface speeds evaporation of water
B—Diurnal land/water surfaces unevenly heated and cooled
C—Air lifted by terrain and cooled
D—Air lifted by riding up over another air mass and cooled.
E—Convection and circulation currents carry air to a colder or warmer surrounding area
F Air cooled from above or below by terrestrial radiation loss.

Figure 2-2. Factors Affecting Hydrologic Cycle.

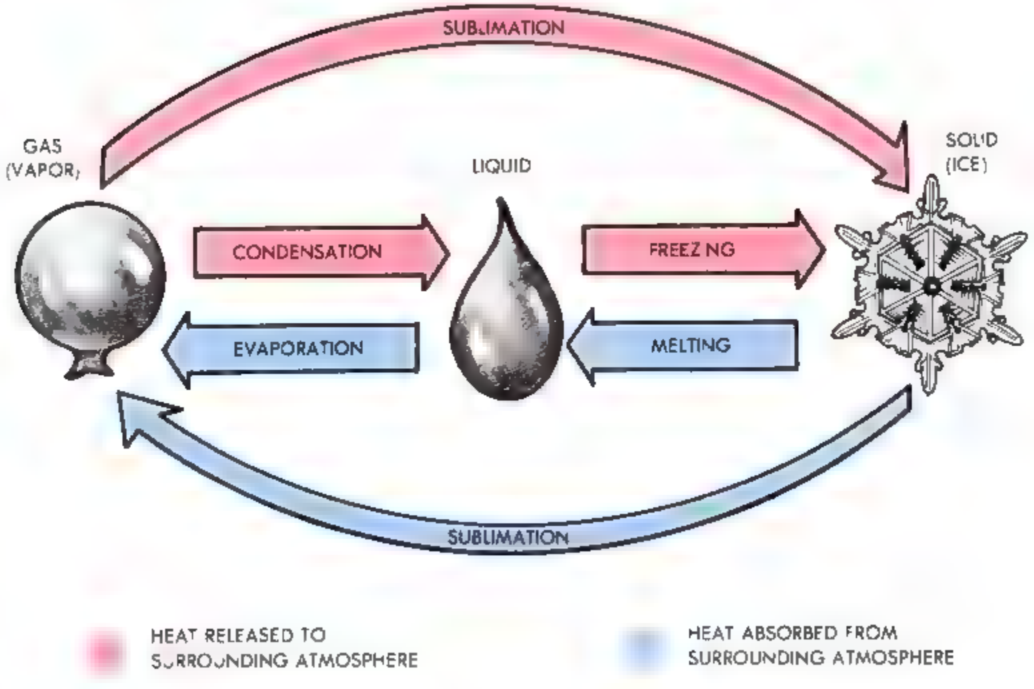


Figure 2-3

Figure 2-3. Changes of State of Water.

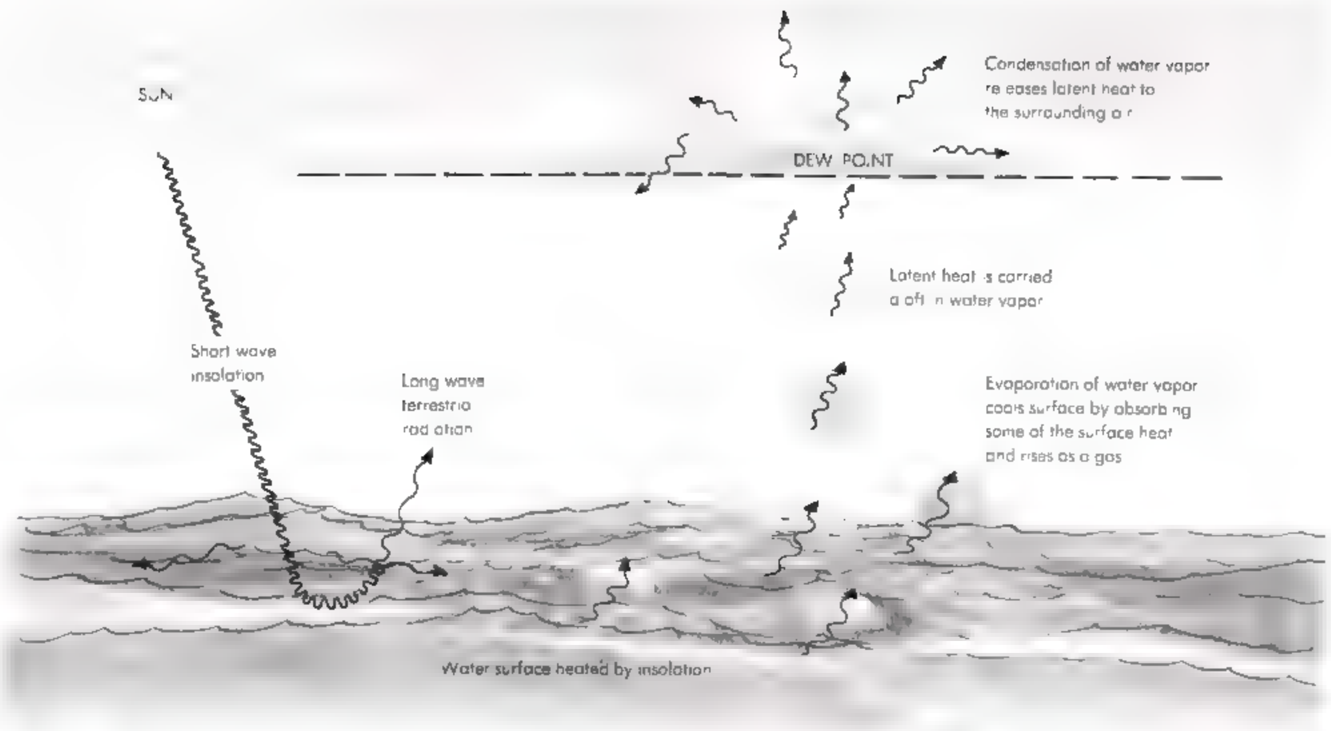

SUN
DEW POINT
Condensation of water vapor releases latent heat to the surrounding air
Latent heat is carried aloft in water vapor
Short wave insolation
Long wave terrestrial radiation
Evaporation of water vapor cools surface by absorbing some of the surface heat and rises as a gas
Water surface heated by insolation

Figure 2-4. Evaporation and Condensation.

amount of heat given off in a thunderstorm during the process of precipitating one-half inch of rain over a square mile is 17 trillion calories. The energy given off by the first atomic bomb dropped in Japan was 20 trillion calories. Melting, freezing, and sublimation from ice to water vapor all involve the exchange of heat in a similar manner.

MOISTURE CONTENT

There is a limit to the amount of water vapor that air, at a given temperature, can hold. When this limit is reached, the air is said to be *saturated*. The warmer the air temperature, the more water vapor the air can hold before saturation is reached and condensation occurs (figure 2-5). For approximately every 20°F (11°C) increase in temperature, the capacity of a volume of air to hold water vapor is about doubled. Unsaturated air, containing a given amount of water vapor, will become saturated if its temperature decreases sufficiently; further cooling forces some of the water vapor to condense as fog, cloud, or precipitation.

Relative Humidity

Relative humidity is the ratio of the amount of water vapor actually in the air to the maximum amount the air can hold at that temperature. When the air contains all of the water vapor possible for it to hold at its temperature, the relative humidity is 100 percent (figure 2-6). A relative humidity of 50 percent indicates that the air contains half of the water vapor which it is capable of holding at its temperature.

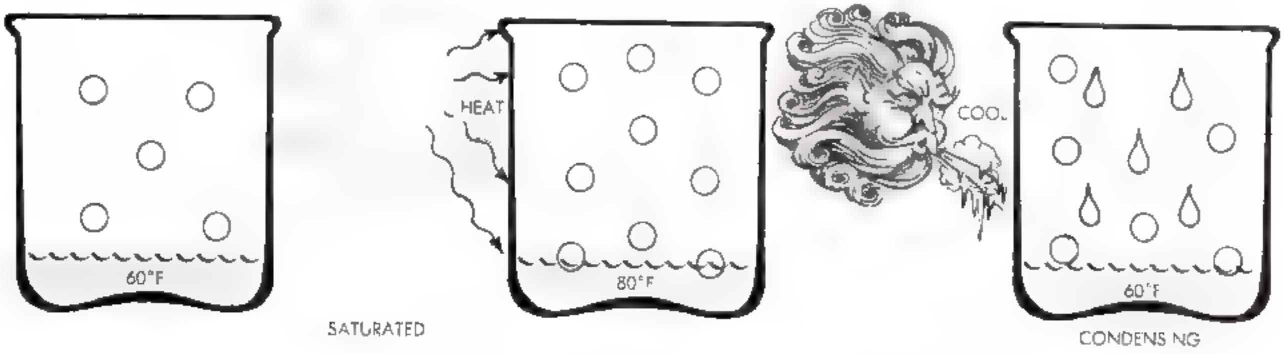


Figure 2-5. Saturation Of Air Depends On Its Temperature.

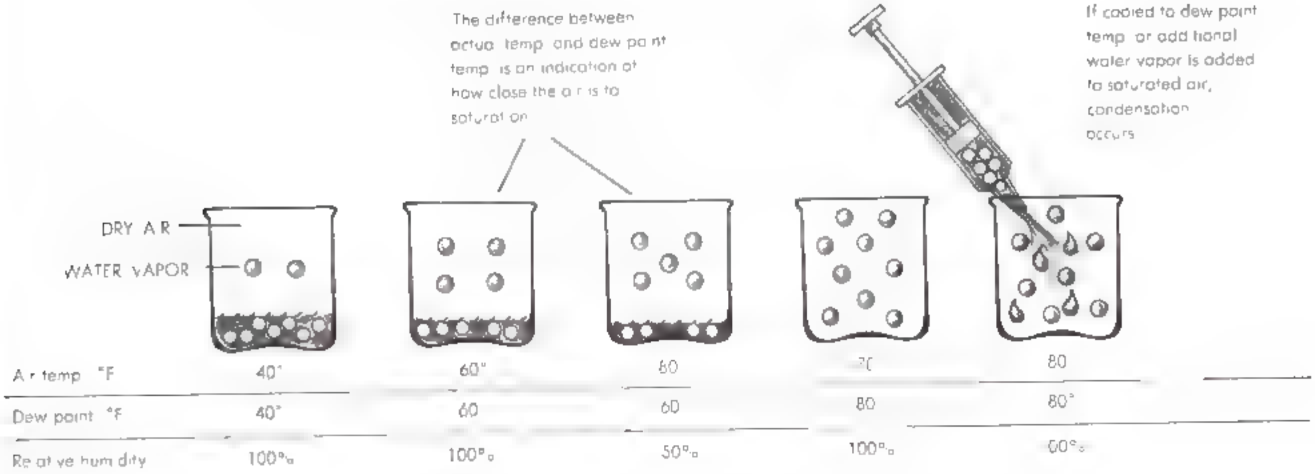

The difference between actual temp and dew point temp is an indication of how close the air is to saturation
If cooled to dew point temp or additional water vapor is added to saturated air, condensation occurs
DRY AIR
WATER VAPOR
Air temp °F
40°
60°
60
80
80
Dew point °F
40°
60
60
80
80°
Relative humidity
100%
100%
50%
100%
100%

Figure 2-6. Relative Humidity and Dew Point.

Dew Point

The *dew point* is the temperature, at a given atmospheric pressure, to which air must be cooled to become saturated (figure 2-6). When this temperature is below freezing, it is sometimes called the *frost point*. The difference between the actual air temperature and the dew point temperature is an indication of how close the air is to saturation. This temperature difference is commonly called the *spread*, or *dew point depression*. Relative humidity increases as the temperature spread decreases and is 100 percent when the spread is 0°. The dew point is included in aviation weather reports because it is a critical temperature, indicating the behavior of water in the atmosphere

Aircrews should be alert for the possibility of fog or low cloud formation at any time when the surface air temperature is within 4°F of the dew point, and the spread between the two is decreasing (figure 2-7). On the other hand, when the surface air temperature is higher than the dew point, and the difference between the surface air temperature and the dew point temperature is increasing, any existing fog and low clouds are likely to dissipate because the air is becoming capable of holding more water vapor. This is especially true in the morning hours when air temperature near the ground is increasing.

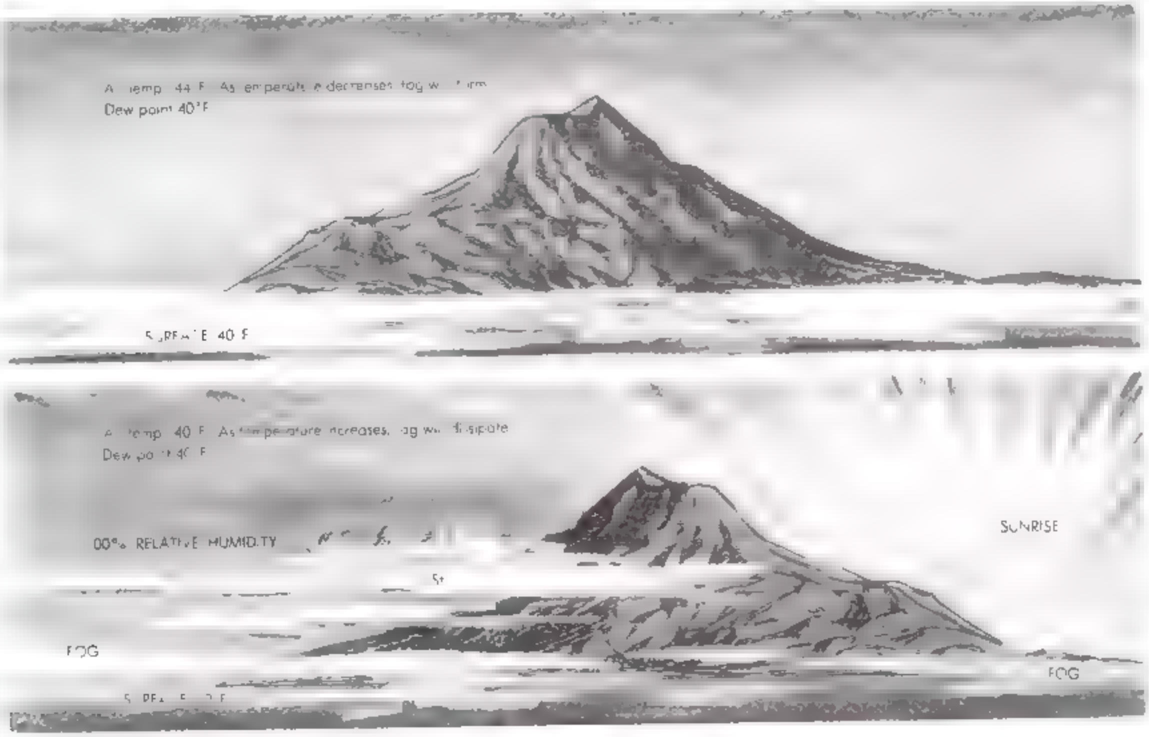

Air temp 44°F As temperature decreases fog will form
Dew point 40°F
SURFACE 40°F
Air temp 40°F As temperature increases, fog will dissipate
Dew point 40°F
100% RELATIVE HUMIDITY
St
SUNRISE
FOG
FOG
SURFACE 40°F

Figure 2-7. Dew Point and Temperature Spread.

CONDENSATION AND SUBLIMATION PRODUCTS

Condensation occurs if moisture is added to the air after saturation has been reached, or if cooling of the air reduces the temperature to the saturation point. As shown in figure 2-8, the most frequent cause of condensation is cooling of the air and often results when: (a) air moves over a colder surface, (b) air is lifted (cooled by expansion), or (c) air near the ground is cooled at night as a result of radiational cooling.

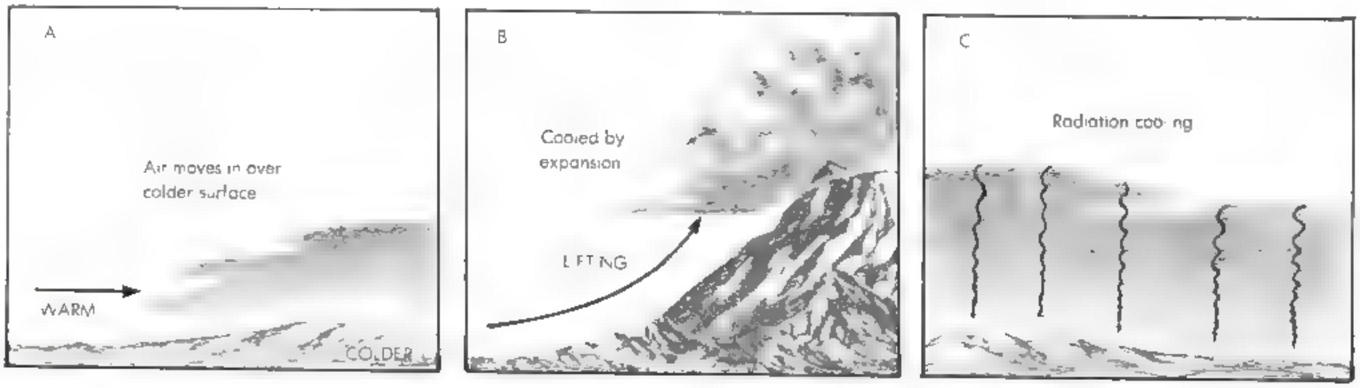


Figure 2-8. Causes of Condensation.

Clouds and Fog

The most common forms of condensation and sublimation products are clouds and fog. Except at temperatures well below freezing, clouds and fog are composed of very small droplets of water which collect on microscopic water-absorbent particles of solid matter in the air called *condensation nuclei*. These include salt from evaporating sea spray, dust, and combustion by-products. Condensation generally occurs as soon as the air becomes saturated

Clouds and fog which form at temperatures well below freezing (-15°C or lower) are usually composed of small particles of ice known as ice crystals, which form directly from water vapor through the process of sublimation. However, liquid water droplets are frequently observed in the atmosphere at temperatures much lower than the freezing point, and while rarely below -40°C, they are known to exist in temperatures near - 50°C. This situation, called supercooling, is prevalent in clouds to a temperature of about -15°C. Aircraft penetrating supercooled clouds are likely to accumulate ice because the impact of the aircraft may induce freezing of the droplets.

Precipitation

Precipitation is liquid or solid moisture that falls from the atmosphere in the form of rain, drizzle, ice pellets, snow, or combinations of them As shown in figure 2-9, the form of precipitation is largely dependent upon temperature conditions and the degree of turbulence present. Although there can be no precipitation without clouds, most clouds do not precipitate.

Initial cloud particles are usually very small and remain suspended in the atmosphere. Precipitation occurs when these particles grow sufficiently in size and weight to fall because of the gravitational pull of the earth. This growth can occur through a number of processes. Once a water droplet or ice crystal forms, it continues to grow by added condensation or sublimation directly onto the particle. This is a slow process and usually results in drizzle or very light rain or snow

In clouds with above freezing temperatures, collision of droplets of varying size is the most common process that produces precipitation. Vertical air currents cause the droplets to collide and assist in the growth of clouds by carrying water droplets to higher altitudes (figure 2-10). Usually, precipitation of other than light intensity requires the cloud to be more than 4,000 feet thick

If vertical currents in clouds are very strong, the supercooled water droplets or ice particles may be carried to high altitudes Since these droplets become very large before and during their fall, the resulting rain or snow is heavy.

Precipitation can change its state as the temperature of its environment changes. For example, falling snow may melt in warmer layers of air at low altitudes to form rain, or rain may fall into cooler layers and freeze into ice pellets before reaching the ground.

Sometimes strong, vertical currents sustain large, supercooled water drops until some freeze, subsequently, other drops freeze to them forming hailstones.

Not all precipitation reaches the earth. On many occasions, it evaporates completely in dry air beneath the cloud base. This is known as virga and is a relatively common occurrence in hot, dry areas such as the southwestern United States.

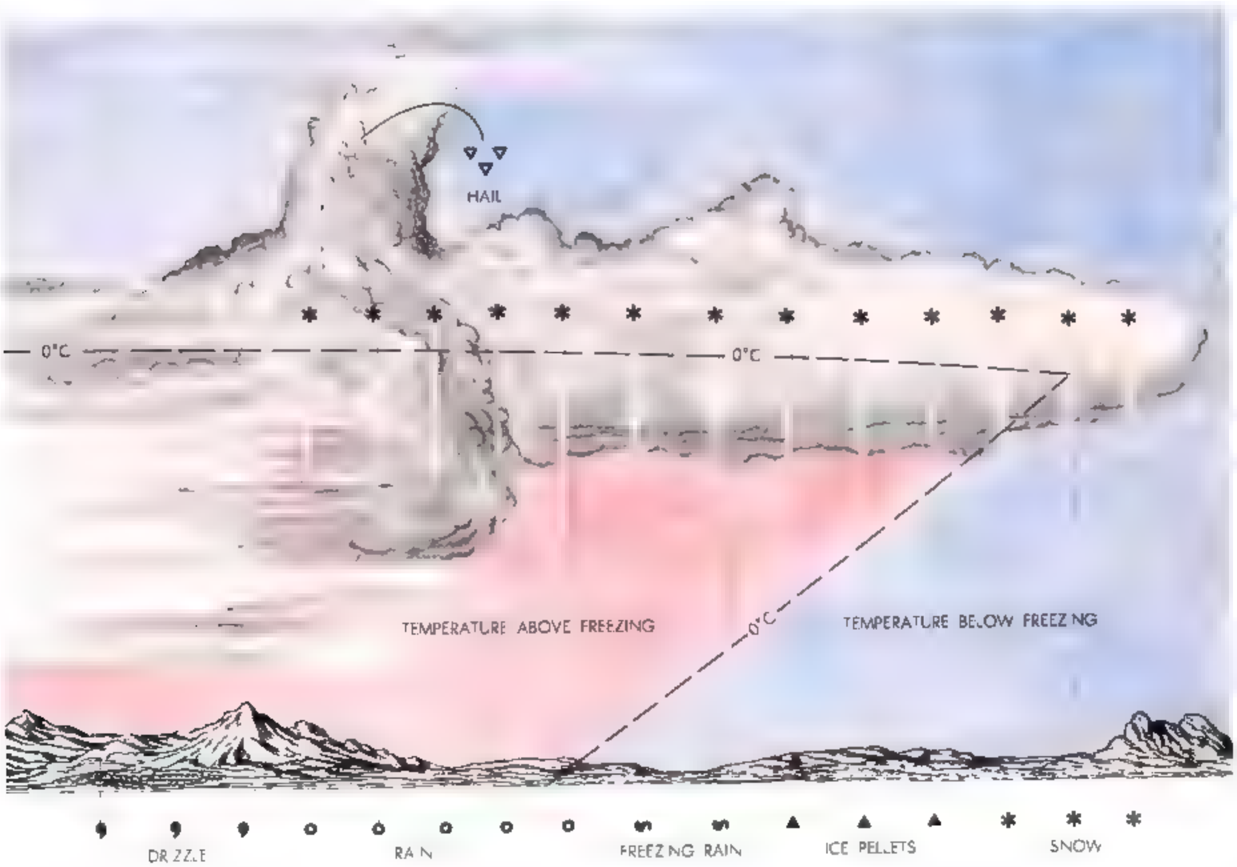


Figure 2-9. Precipitation Products.

Dew and Frost

During clear, still nights, aircraft surfaces often cool by radiation to a temperature equal to the dew point of the adjacent air. Moisture then collects on the surface just as it does on a pitcher of ice water in a warm room. The moisture comes from the air in direct contact with the cool surface. Often heavy dew is observed on grass or plants when there is none on the pavements or on large, solid objects. Since large objects absorb so much heat during the day, their temperature falls slowly, and their temperature may not cool below the dew point of the surrounding air during the night (figure 2-11).

Frost forms in much the same way as dew. The difference is that the dew point of the surrounding air must be colder than freezing. Water vapor then sublimates directly as ice crystals or frost rather than condensing as dew. Sometimes dew forms and later freezes, but frozen dew is easily distinguishable from frost since it is transparent and frost is opaque.

Aircrew members must not underestimate the flight hazards of dew or frost formation The dew may freeze on the surface of the aircraft when it passes through a subfreezing air mass, resulting in increased drag and decreased lift

Remove *all* frost from the aircraft before takeoff. In flight, frost can be removed by flying into very cold temperatures aloft or melted by flying into a layer of warm air.

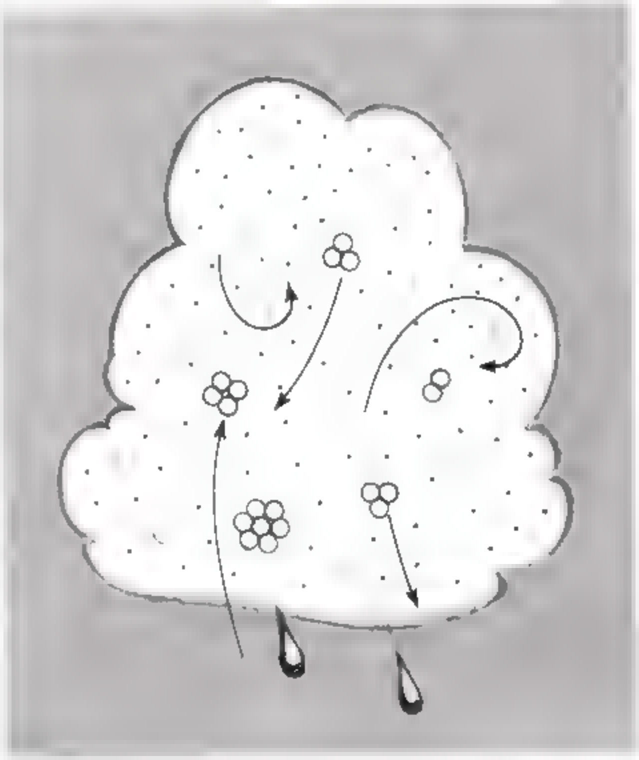
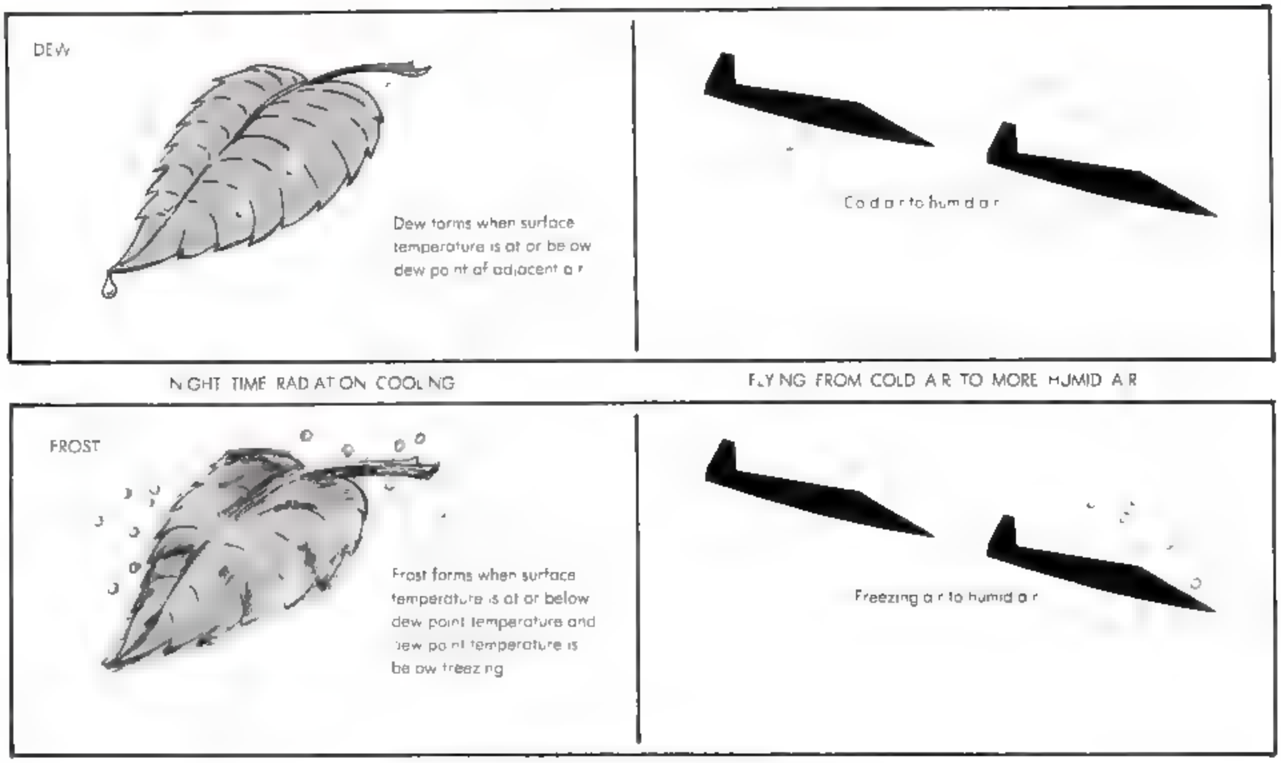


Figure 2-10. Growth of Raindrops by Collision of Cloud Droplets.


DEW
Cold air to humid air
NIGHT TIME RADIATION COOLING
FLYING FROM COLD AIR TO MORE HUMID AIR
FROST
Freezing air to humid air

Dew forms when surface temperature is at or below dew point of adjacent air

Frost forms when surface temperature is at or below dew point temperature and dew point temperature is below freezing

Figure 2-11. Dew or Frost Formation.

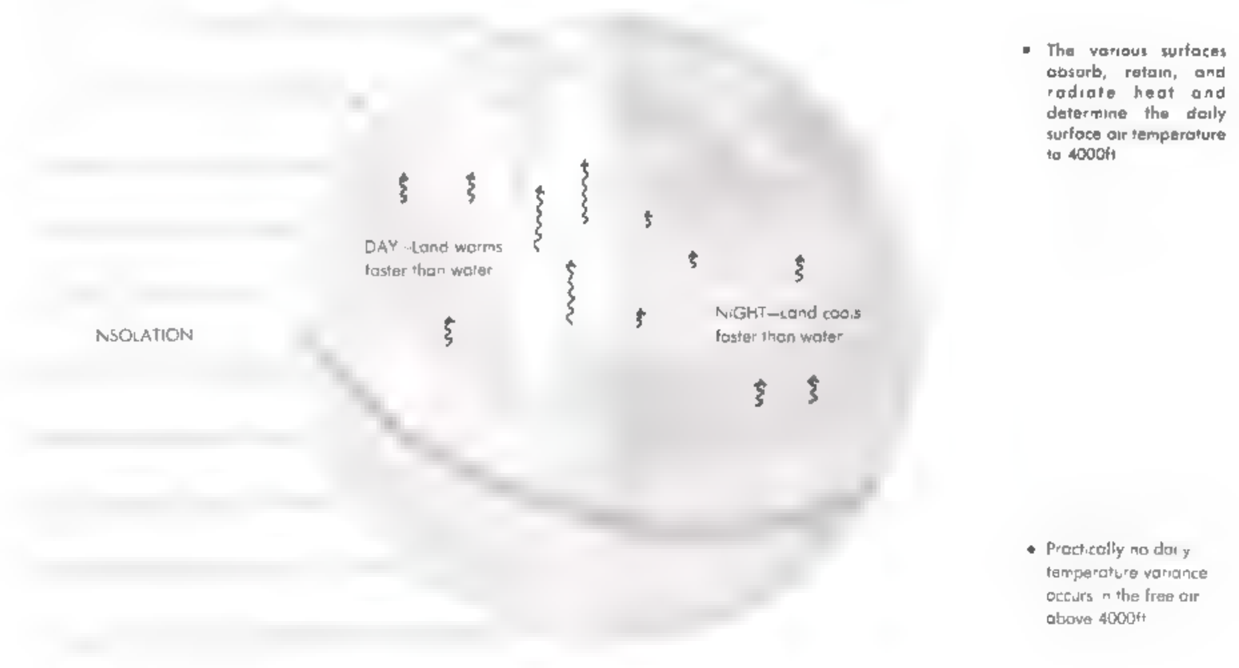
CHAPTER 3

TEMPERATURE

Temperature is important to the aircrew because it enters into the computation of most aircraft performance parameters. In fact, temperature can be critical to some flight operations This chapter relates heat and temperature, describes commonly used temperature scales, and surveys temperature variations both at the surface and aloft.

Temperature is a measurement of heat energy and expresses the degree of molecular activity. Since different substances have different molecular structures, equal amounts of heat applied to equal volumes of two different substances will cause one substance to get hotter than the other. For example, a land surface becomes hotter than a water surface when equal amounts of heat are added to each (figure 3-1). The degree of "hotness" or "coldness" of a substance, as measured with a thermometer, is known as its temperature.

The sun heats the earth's surface during the day Incoming solar radiation to the earth is called *insolation*. Heat is radiated from the earth by outgoing radiation, called *terrestrial radiation*. Cooling results at night as terrestrial radiation continues and insolation ceases



INSOLATION
DAY—Land warms faster than water
NIGHT—Land cools faster than water

- The various surfaces absorb, retain, and radiate heat and determine the daily surface air temperature to 4000ft
- Practically no daily temperature variance occurs in the free air above 4000ft

Figure 3-1. Land Has Greater Temperature Variance Than Water.

TEMPERATURE MEASUREMENT

Fahrenheit and Celsius (centigrade) are the names given to the two temperature scales important to the aircrew member. On the Fahrenheit (F) scale, the freezing point is at 32° and the boiling point at 212° - a difference of 180° (figure 3-2). On the Celsius (C) scale, the freezing point is at 0° and the boiling point at 100° - a difference of 100°. The ratio between °F and °C is, therefore, 180 to 100, or 9 to 5. This means that a temperature difference of 9°F is equal to a temperature difference of 5°C. This ratio is used in converting from one scale to another as shown below and in figure 3-2.

$$°C = \frac{5}{9}\,(°F - 32)$$

$$°F = \frac{9}{5}\,°C + 32$$

Many air navigation computers are marked for direct conversion between Fahrenheit and Celsius. The temperatures considered in aviation weather are those of the free air. The temperature measuring elements are exposed in a manner that avoids direct sunlight and minimizes other effects that cause inaccuracies in the readings.

The measurement of outside air temperatures with the typical aircraft thermometer is influenced by several factors (such as radiation, air compression, and friction) which tend to decrease the accuracy of these observations. Such effects may cause the reading to differ from the true free-air temperature by 25°F (14°C) or more, except where careful engineering has been provided Most flight manuals contain a temperature correction chart to obtain true air temperature.

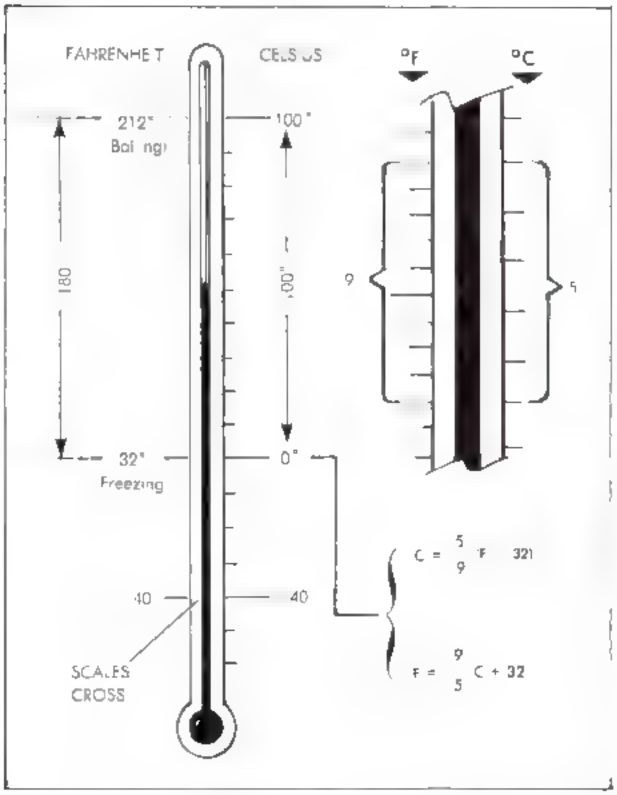


Figure 3-2. Temperature Conversion Methods.

DAILY RANGE OF TEMPERATURE

Diurnal variation is the change in temperature from day to night caused by the daily rotation of the earth During the day incoming solar radiation exceeds outgoing terrestrial radiation and the surface be comes warmer At night, solar radiation ceases, but terrestrial radiation continues and cools the surface Minimum temperature usually occurs just after sunrise The continued cooling after sunrise is one reason that fog sometimes forms shortly after the sun is above the horizon.

The range of temperature between night and day varies considerably, both with season and location. The daily variance ranges as much as 30° to 50°F. It is greater near the surface of barren high-level places, over sand, plowed fields, and rocks, while it is much smaller over thick vegetation and deep water surfaces Practically no change of temperature occurs between night and day in the free air 4,000 feet or more above the surface within the troposphere.

The temperature (and resultant air density) at and near the surface greatly affects aircraft allowable gross weights for both takeoff and landing. An aircraft taking off during night or early morning when the cooler air is dense generally has more allowable gross weight than it would have in the early afternoon when the air has warmed and become less dense

TEMPERATURE DISTRIBUTION

Surfaces

The temperature distribution over the surface of the earth depends first on the seasons and secondly on the composition and distribution of land and sea surfaces over the earth. Figure 3-3 shows the surface temperature distribution for January (A) and July (B) representing both hemispheres' winter and summer respectively and clearly illustrates the influence of topography on the temperature. The following pertinent information can be noted.

- The ocean areas between latitudes 40°N and 40°S show very little temperature changes from summer to winter
- The land areas are warmer than the adjacent water areas at the same latitude during summer
- The water areas are warmer than the adjacent land areas at the same latitude during winter.
- Both the warmest and coldest temperatures are found over the land areas

Aloft

Aircrew members are concerned with temperatures aloft in selecting flight altitudes, in determining allowable gross weight, and for other reasons affecting the flight.

TEMPERATURE VARIATION WITH ALTITUDE

Temperature normally decreases with increasing altitude throughout the troposphere. This decrease of temperature with altitude is called the *lapse rate* and is usually expressed in degrees per thousand feet. The standard lapse rate in the troposphere is 2°C (3½°F) per 1,000 feet This value serves as the basis for calibrating aircraft instruments and preparing performance charts. Figure 3-4 shows nonstandard temperature effects on pressure and density.

Temperature Inversions

Variation in the lapse rate may change with altitude itself (figure 3-5). At a given time and place, for example, the temperature might decrease at a rate of 3°C per 1,000 feet from the ground to an altitude of 5,000 feet, at a rate of 1°C per 1,000 feet between 5,000 and 7,000 feet, and at 2°C per 1,000 feet above 7,000 feet until the tropopause is reached

Many times there is a layer within the troposphere which is characterized by an increase of temperature with altitude rather than a decrease. This situation occurs frequently but is usually confined to a relatively shallow layer. It is called an *inversion* because the usual decrease in temperature with altitude is inverted

The most frequent type of inversion over land is that produced immediately above the ground on a clear, relatively still night. The ground loses heat rapidly through terrestrial radiation, cooling the layer of air next to it. The amount of cooling decreases rapidly with altitude, and the temperature of the air a few hundred feet above the ground is affected very little or not at all. Terrestrial radiation thus causes the lowest layer of air to be colder than the air just above that layer. If skies are overcast, nighttime cooling is reduced, and it is unlikely the radiation inversion will form

Inversions are also found in association with movement of colder air under warm air or the movement of warm air over cold air Such inversions are often called frontal inversions Their formation will be discussed in the chapter on fronts

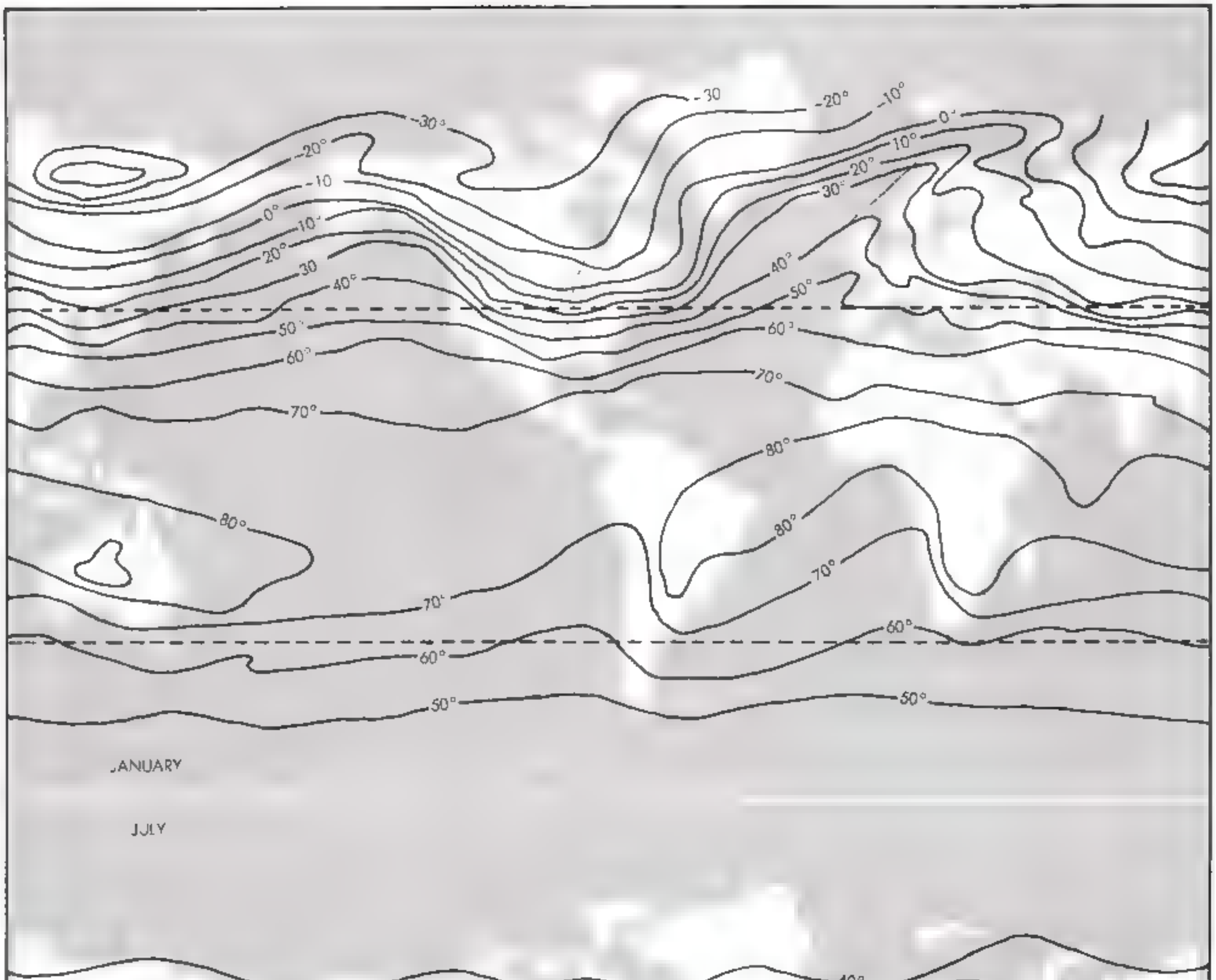
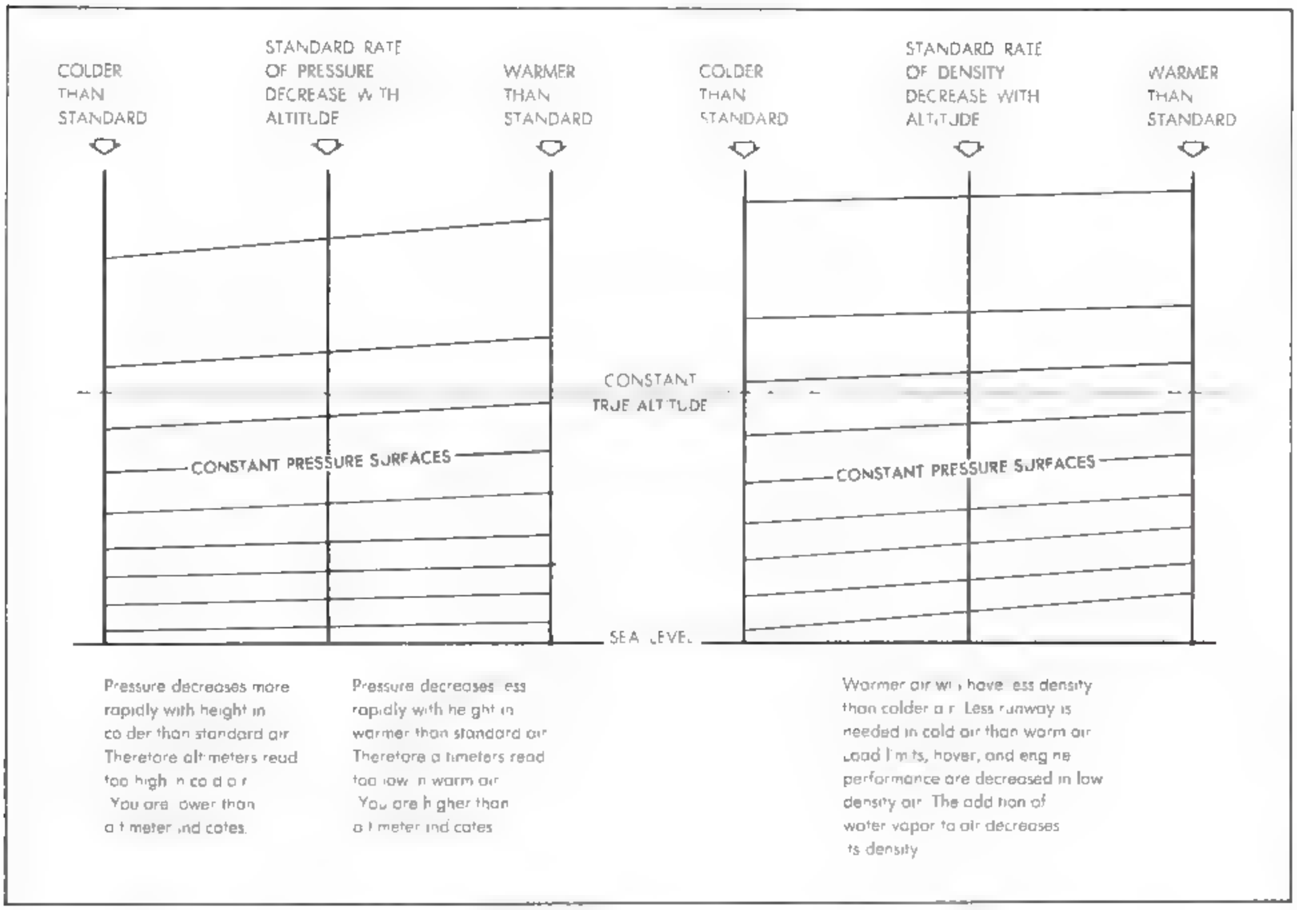


Figure 3-3. Surface Temperature Distribution for January-July.


COLDER THAN STANDARD
STANDARD RATE OF PRESSURE DECREASE WITH ALTITUDE
WARMER THAN STANDARD
COLDER THAN STANDARD
STANDARD RATE OF DENSITY DECREASE WITH ALTITUDE
WARMER THAN STANDARD
CONSTANT TRUE ALTITUDE
CONSTANT PRESSURE SURFACES
CONSTANT PRESSURE SURFACES
SEA LEVEL

Pressure decreases more rapidly with height in colder than standard air. Therefore altimeters read too high in cold air. You are lower than altimeter indicates.

Pressure decreases less rapidly with height in warmer than standard air. Therefore altimeters read too low in warm air. You are higher than altimeter indicates.

Warmer air will have less density than colder air. Less runway is needed in cold air than warm air. Load limits, hover, and engine performance are decreased in low density air. The addition of water vapor to air decreases its density.

Figure 3-4. Effect of Nonstandard Temperature on Pressure and Density.

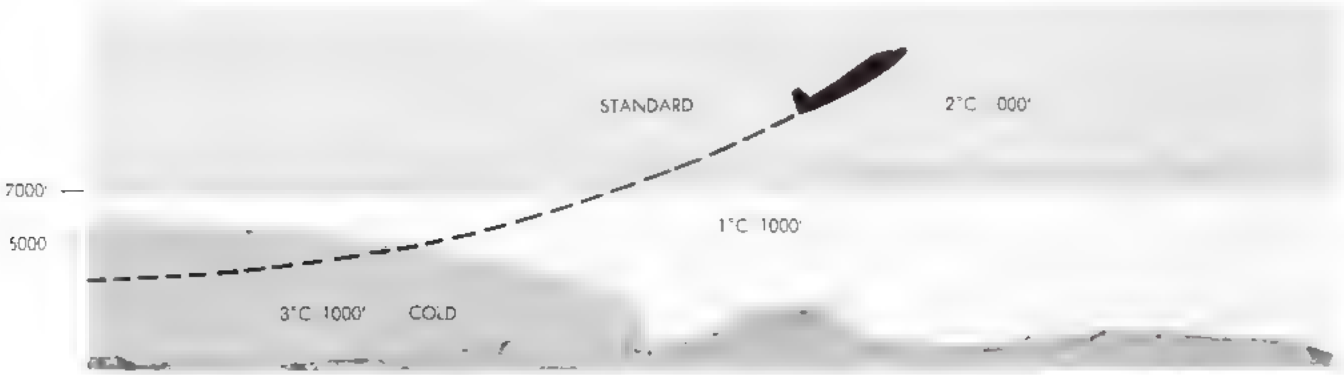


Figure 3-5. Lapse Rates May Vary From Layer To Layer.

An inversion sometimes forms as a result of widespread sinking of air (subsidence) within a relatively thick layer aloft, while the air below this layer is essentially unchanged. This sinking air is heated by compression, and it may become warmer than the air below it.

Figure 3-6 illustrates a ground (surface-based) inversion and an inversion aloft. Restrictions to vision, such as fog, haze, smoke, and low clouds, are often found in or below low inversions and in layers through which there is only a small change in temperature. The air in these layers is usually very smooth; however, turbulence may be expected between the layers.

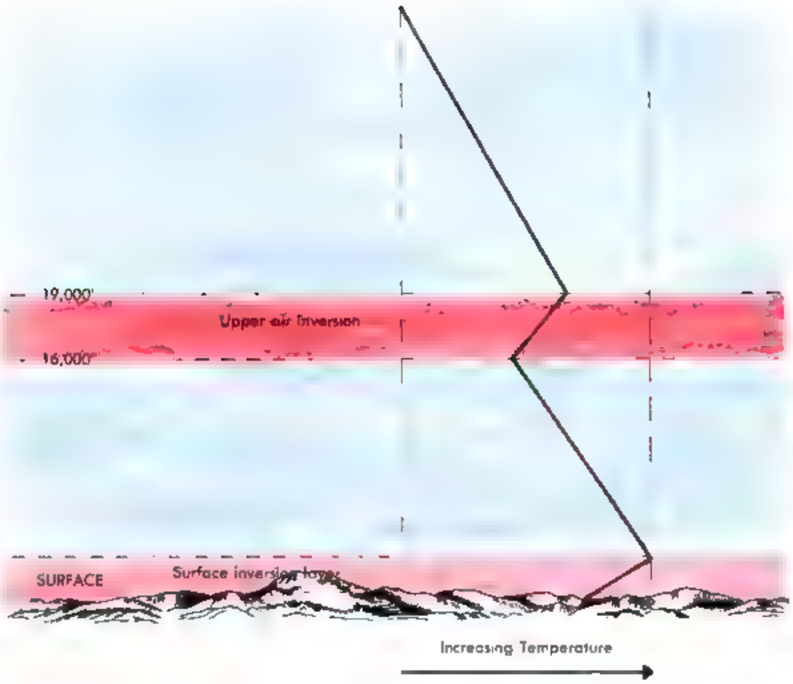


Figure 3-6. Lapse Rate Temperature Reversals Are Called Inversions.

CHAPTER 4

ATMOSPHERIC PRESSURE AND ALTIMETRY

Atmospheric pressure is the force-per-unit area exerted by the weight of a column of air lying directly above a point. As a result of the constant and complex air movements and the changes in temperature and moisture content of the air, the weight of this column over a fixed point is continually fluctuating. These changes in weight, and therefore pressure, are measured with pressure-sensitive instruments called barometers. Weather services and crew members use two types of barometers - the mercurial and the aneroid.

THE MERCURIAL BAROMETER

The mercurial barometer, shown in figure 4-1, consists of an open dish of mercury into which is placed the open end of an evacuated glass tube. Atmospheric pressure forces mercury to rise in the tube. At stations near sea level, the column of mercury rises on the average to a height of 29.92 inches or 760 millimeters In other words, a column of mercury that height weighs the same as a column of air having the same cross section as the column of mercury and extending from sea level to the top of the atmosphere.

The advent of aviation early in this century brought about a search for an accurate method of measuring the altitude at which an aircraft was flying. Barometric pressure was ideal for several reasons, chiefly the fact that the change in pressure with altitude is approximately 10,000 times greater than that found in equivalent horizontal distances. The rate of change in vertical heights in the lower atmosphere is about 1 inch for every 1,000 feet of altitude.

However, the mercurial barometer, while the most accurate in the measurement of pressure, proved too bulky and delicate to carry about on aircraft. It was also difficult to read because it indicated inches of mercury rather than feet of altitude.

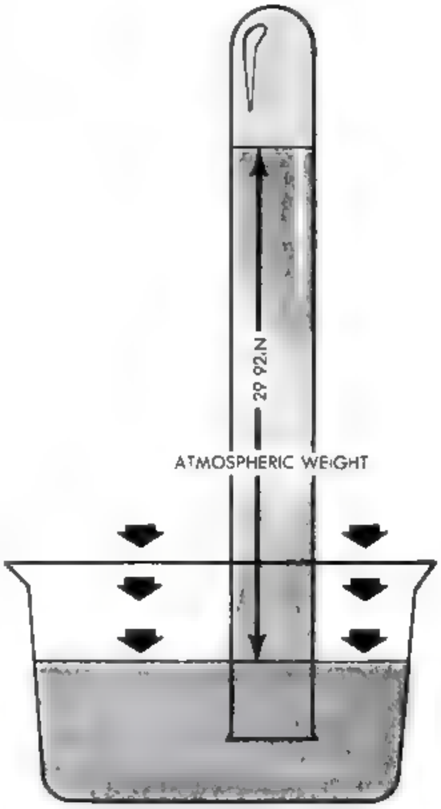


Figure 4-1. Normal Atmospheric Pressure At Sea Levels Supports A Column Of Mercury 29.92 Inches High.

THE ANEROID BAROMETER

The necessity for a more convenient and sturdy pressure instrument resulted in the aneroid (meaning "containing no fluid") barometer (figure 4-2). In short, the cell, made of thin metal to make it flexible, is partially evacuated of air so that it will respond more readily to changes of atmospheric pressure One end of the cell is fixed, while the other end is coupled to a pointer on a dial marked with pressure readings expressed in feet. The coupling itself magnifies the movement of the free end of the cell so as to express its calibration of 1,000 feet of altitude to each 1 inch of barometric change, using as a base the standard sea level barometric pressure of 29.92 inches of mercury.

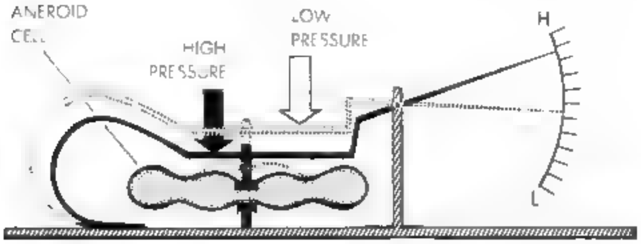


Figure 4-2. Aneroid Barometer.

PRESSURE UNITS

Pressure is expressed in many ways throughout the world. The two most common units are inches of mercury (Hg) and millibars. Since the Kollsman window of pressure altimeters in United States aircraft is calibrated for settings in inches of mercury, United States military and civil weather agencies express altimeter settings in inches of mercury

However, inches of mercury do not directly express pressure in terms of *force-per-unit area.* A common unit of pressure that does is the millibar (mb), a unit of measurement equal to a force of 1,000 dynes per square centimeter Many foreign nations use the millibar for altimeter settings. Crew members flying in these countries can consult the appropriate Enroute Supplement or the Flight Information Publication (FLIP) for a conversion table of millibars to inches of mercury. The standard atmospheric pressure at sea level in millibars is 1013.2, which corresponds to 29.92 inches of mercury

PRESSURE DISTRIBUTION

Figure 4-3 shows the average worldwide distribution of sea level pressure for the months of January and July, representing Northern Hemisphere winter and summer respectively. Some of the more important features are listed below:

- The semipermanent belt of high pressure located in the subtropical ocean regions of both hemispheres (20° to 30° latitude) is usually present during both January and July.
- The subtropical belt of high pressure normally extends northward into Siberia and continental North America during January and disappears during July.
- Deep lows are normally present in the Northern Pacific Ocean (the Aleutian low) and the North Atlantic Ocean (the Icelandic low) in January.
- Low pressure usually dominates the land areas of the Southern Hemisphere during both January and July.

PRESSURE VARIATIONS

Pressure variations are continually occurring at any given location with occasional abrupt changes due to thunderstorms and fronts and more gradual variations on a weekly, monthly, and seasonal basis The passage of well-developed pressure systems (either highs or lows) is often accompanied by a change in pressure, but a one-inch change, for example, may take several hours to occur. Pressure varies most with altitude and temperature of the air.

Altitude

The biggest change in barometric pressure comes with height. Within the lower few thousand feet of the troposphere, where most of the atmosphere is concentrated because of gravity, the change amounts roughly to 1 inch of mercury for each 1,000 feet of altitude. Thus, an observer at a station located 5,000 feet above sea level would get a reading of approximately 24.92 inches (figure 4-4). Since all stations are not at the same elevation and conditions vary, the *observed station pressure is adjusted to sea level pressure for reporting purposes.* If this were not done, Denver, for instance, would always report a lower pressure than New Orleans.

Temperature

Air expands as it becomes warmer and contracts as it cools. Figure 4-5 shows three columns of air - one colder than standard, one at standard temperature, and one warmer than standard. Pressure is equal at the bottom of each column and at the top of each column. Vertical expansion of the warm column makes it higher than the column at standard temperature. Contraction of the cold column makes it shorter. Since pressure decrease is the same in each column, the rate of decrease of pressure with height in warm air is less than standard. The rate of decrease of pressure with height in cold air is greater than standard

PRESSURE PATTERNS

Atmospheric pressure readings are used quite extensively by weather forecasters and aircrew members. Pressure patterns on weather charts are analyzed to give insight to observed weather and expected changes. The relationship between pressure systems and weather is complicated, and only a trained meteorologist is expected to understand the relationship thoroughly However, there are numerous pressure patterns that aircrew members should recognize on weather charts because they are necessary to understand some of the weather causes and effects For example, there is a direct relationship between pressure systems and the flow of air (wind), and in general, high pressure areas are typically regions of favorable weather conditions, while lows are often

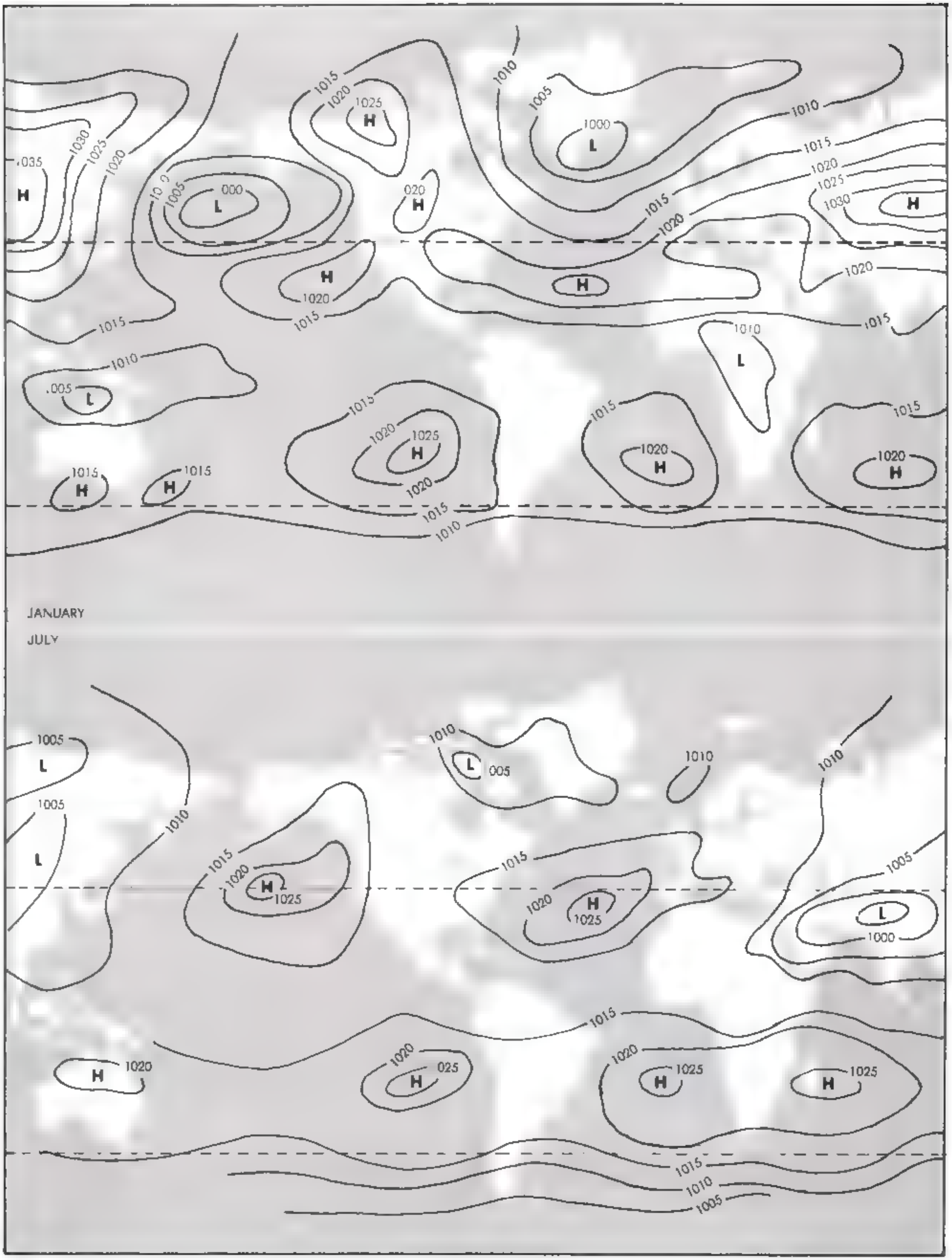


Figure 4-3. Prevailing Pressure Systems Of The World.

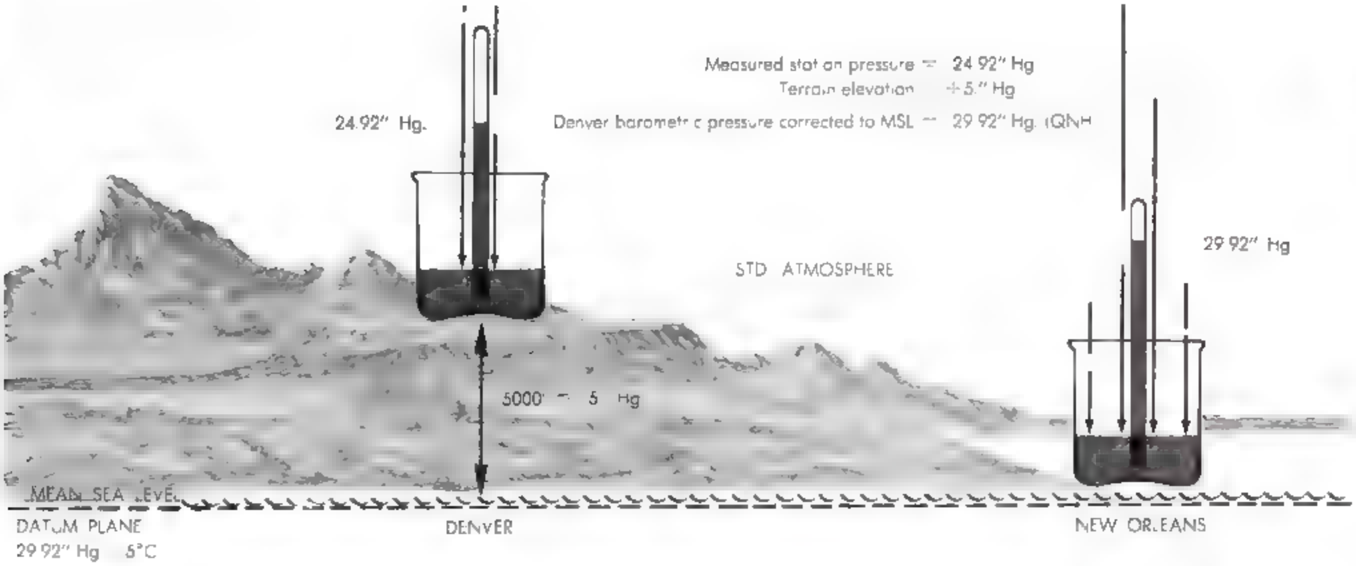

Measured station pressure = 24.92" Hg
Terrain elevation +5." Hg
Denver barometric pressure corrected to MSL = 29.92" Hg (QNH
24.92" Hg.
29.92" Hg
STD ATMOSPHERE
5000' = 5" Hg
MEAN SEA LEVEL
DATUM PLANE
29.92" Hg 15°C
DENVER
NEW ORLEANS

Figure 4-4. Adjusting Barometric Pressure To MSL Pressure.

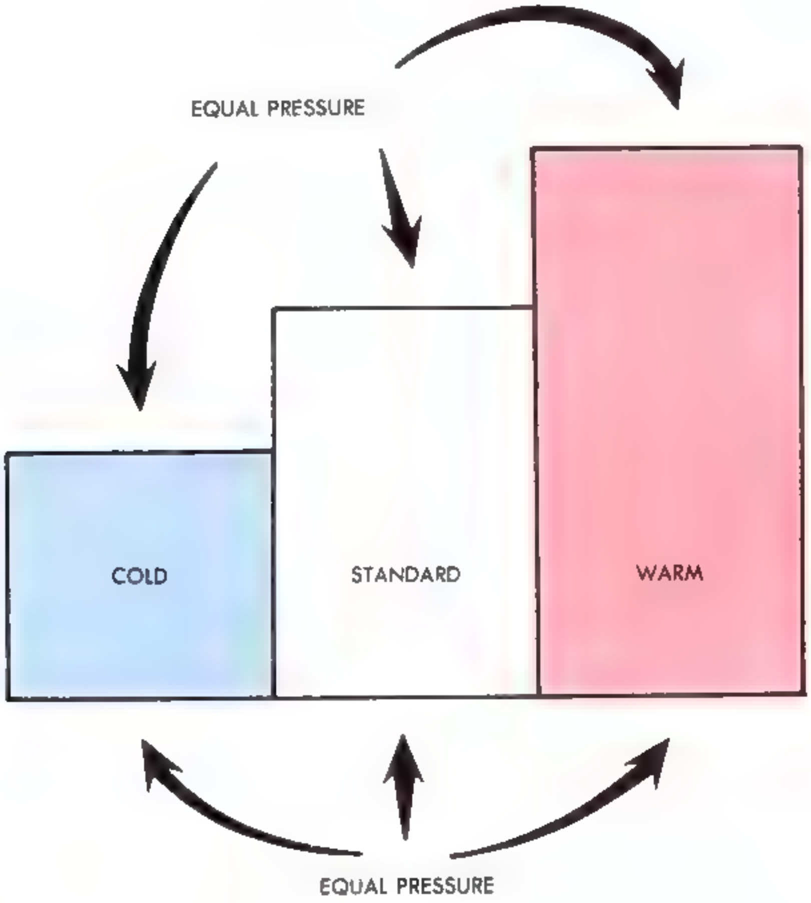


Figure 4-5. Decrease Of Pressure With Height Varies With Temperature.

associated with bad weather. Pressure variations also affect the density of the atmosphere, and therefore they affect flight. The most noticeable effects of decreased pressure due to increased elevation are higher required air speed for takeoffs and landings, increased takeoff and landing roll, decreased rate of climb, and higher stalling speeds.

On surface charts, pressure patterns are shown by a series of lines, called *isobars*, which connect points of equal pressure expressed in millibars (figure 4-6). On constant pressure upper-air charts, these lines, called *contours*, connect points of equal altitude (figure 4-7) expressed in meters. Figure 4-8 shows a comparison of isobars and contours. Other symbols used on these charts are explained below:

- Low - An area of low pressure surrounded on all sides by higher pressure (as outlined by isobars on surface charts) or an area of low true altitude surrounded by higher true altitudes (as shown by contours on upper air charts); also called a cyclone.
- High - An area of high pressure surrounded on all sides by lower pressure (as outlined by isobars on surface charts) or an area of high true altitude surrounded by lower true altitudes (as shown by contours on upper air charts); also called an anticyclone.
- Trough - An elongated area of low pressure with the lowest pressure along a line called a "trough line" which marks the place of maximum curvature in the isobars or contours.
- Ridge - An elongated area of high pressure with the highest pressure along a line called a "ridge line" which marks the place of maximum curvature in the isobars or contours.
- Col - The neutral area between two highs and two lows.

STANDARD ATMOSPHERE

Since the vertical distribution of both temperature and pressure changes with time and place, some convenient vertical structure of the atmosphere, representing average conditions, had to be assumed to obtain a fixed reference point. The International Civil Aviation Organization (ICAO) determined by a year-round average of pressure/height/temperature soundings what is now considered the standard atmosphere for use in calibrating the aneroid barometer. A partial list of values assigned by ICAO to make up the standard atmosphere is as follows:

- A surface temperature of 15°C (59°F) at sea level.
- A surface pressure of 29.92 inches of mercury (1013.2 millibars, 14.7 pounds per square inch) at sea level.
- A lapse rate within the troposphere of approximately 2°C per 1,000 feet.
- A tropopause of approximately 36,000 feet.
- A lapse rate of 0°C in the stratosphere to approximately 82,000 feet.

ALTIMETRY

An aircraft altimeter (figure 4-9) is essentially an aneroid barometer calibrated to indicate altitude in feet instead of units of pressure. This altitude is independent of the terrain below. An altimeter reads accurately only in a standard atmosphere and when the correct altimeter setting is used. Remember, an altimeter is *only* a pressure-measuring device. It will *indicate* 10,000 feet when the pressure is 697 millibars, whether or not the altitude is *actually* 10,000 feet.

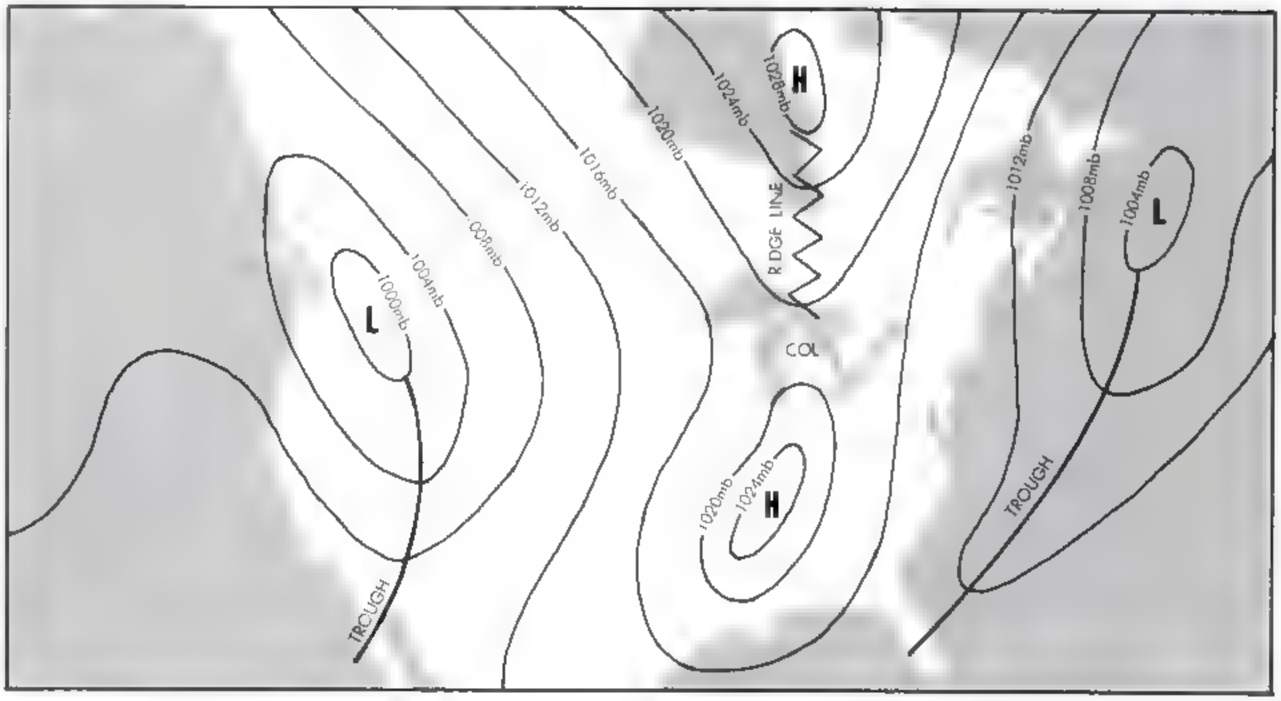


Figure 4-6. Surface Pressure Chart.

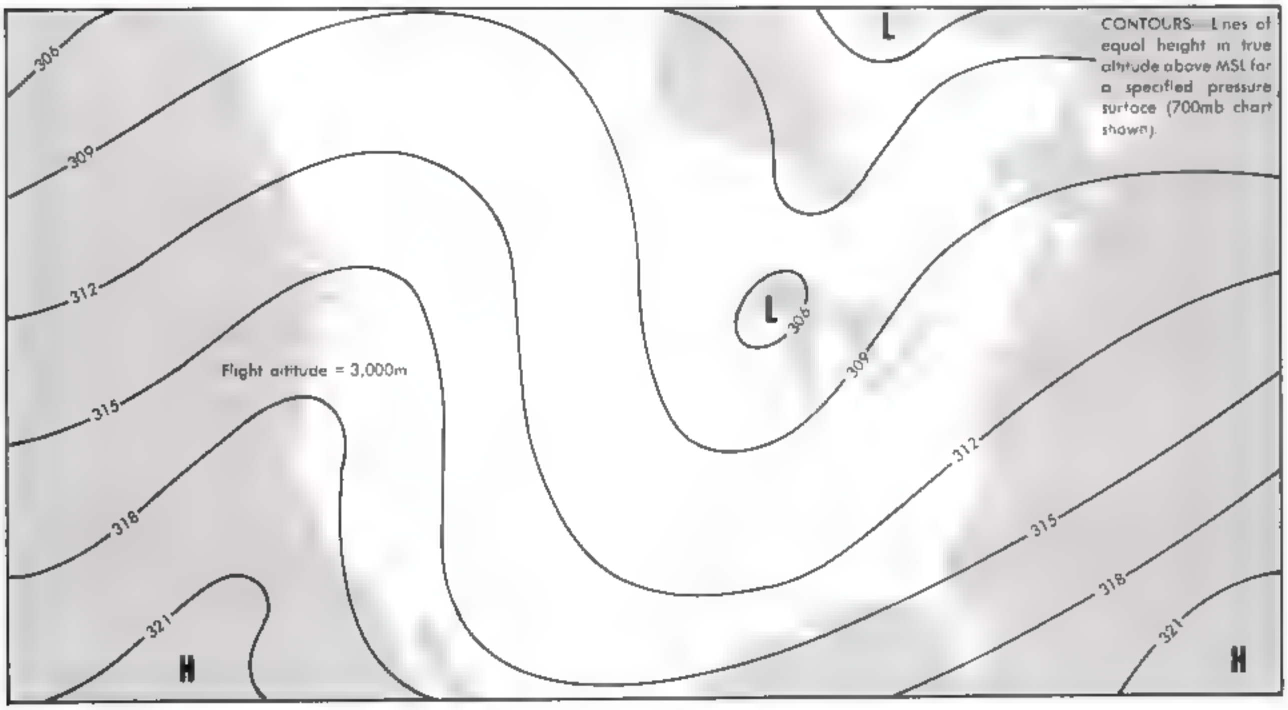

CONTOURS—Lines of equal height in true altitude above MSL for a specified pressure surface (700mb chart shown).
L
L
H
H
306
309
312
315
318
321
306
309
312
315
318
321
Flight altitude = 3,000m

Figure 4-7. Upper Air Chart (700 mb Pressure Surface).

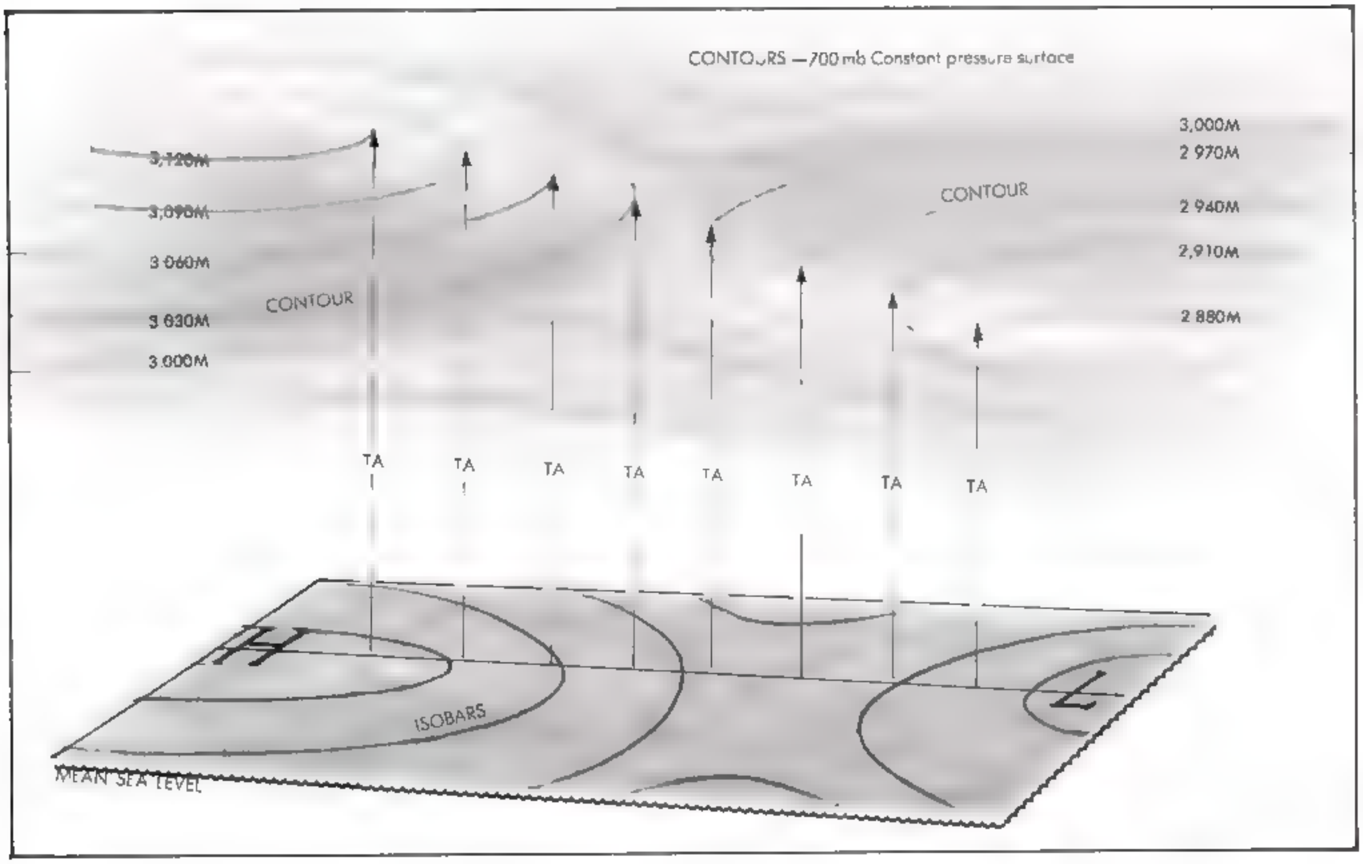
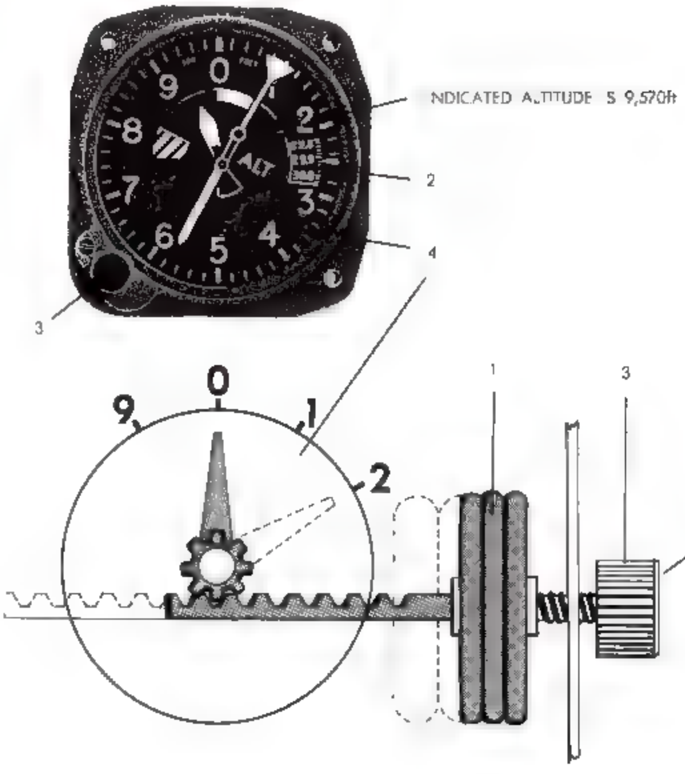


Figure 4-8. Comparison of Isobars and Contours.



1 Aneroid cell expands in low pressure to indicate altitude in feet above MSL in standard atmosphere with reported station pressure set into Kollsman window

2 Barometric scale

3 Barometric pressure set knob

4 Altitude indication scale

- Because surface pressures are always changing, a means of changing the altimeter reference is necessary. A barometric set knob is provided to change the reference shown on the barometric scale and is designed to change the altimeter indication approximately 10 feet for each .01" Hg change on the scale. This approximates the rate of pressure change found in the first 10,000 feet of atmosphere, i.e. 1" Hg for each 1,000 feet.

- Increasing the barometric setting will cause the altitude indication to increase while decreasing the value on the barometric scale will cause the altitude indication to decrease. The majority of altimeters have mechanical stops at or just beyond the barometric scale limits 28.10 to 31.00

Figure 4-9. Aneroid Altimeter.

True Altitude

Since conditions in the real atmosphere are seldom standard, altitude indications on the altimeter are seldom actual or true altitudes. True altitude is the actual or exact altitude above mean sea level.

Indicated Altitude

Refer again to figure 4-5 showing the effect of mean temperature on the thickness of the three columns of air. Since pressure is equal at the base and equal at the top of each column, indicated altitude is the same at the top of each column. To see this effect more clearly, study figure 4-10. Note that in the warm air the aircraft is flying at an altitude higher than indicated. In the cold air the aircraft is at an altitude lower than indicated.

Pressure Altitude

In the standard atmosphere, sea level pressure is 29.92 inches Hg or 1013.2 millibars. This is called the standard datum plane. Pressure falls at a fixed rate upward through this hypothetical atmosphere. Pressure altitude is the altitude above that standard datum plane. Therefore, crew members can easily determine pressure altitude from the aircraft altimeter whether in flight or on the ground. Simply set the altimeter to the standard altimeter setting of 29.92 inches, and the altimeter will indicate pressure altitude.

Altimeter Settings

There are three different altimeter settings. A comparison of the three altimeter settings is listed below:

SETTING	AT AIRPORT	IN THE AIR
Standard QNE 29.92 Hg 1013.25 mb	Variable elevation reading above or below actual elevation	Positive separation by pressure level but at varying actual altitudes
QNH	Actual elevation above sea level reading when aircraft on ground	Altitude of aircraft above sea level (without consideration of temperature)
QFE	Zero elevation reading when aircraft on ground.	Height above ground indicated (without consideration of temperature).

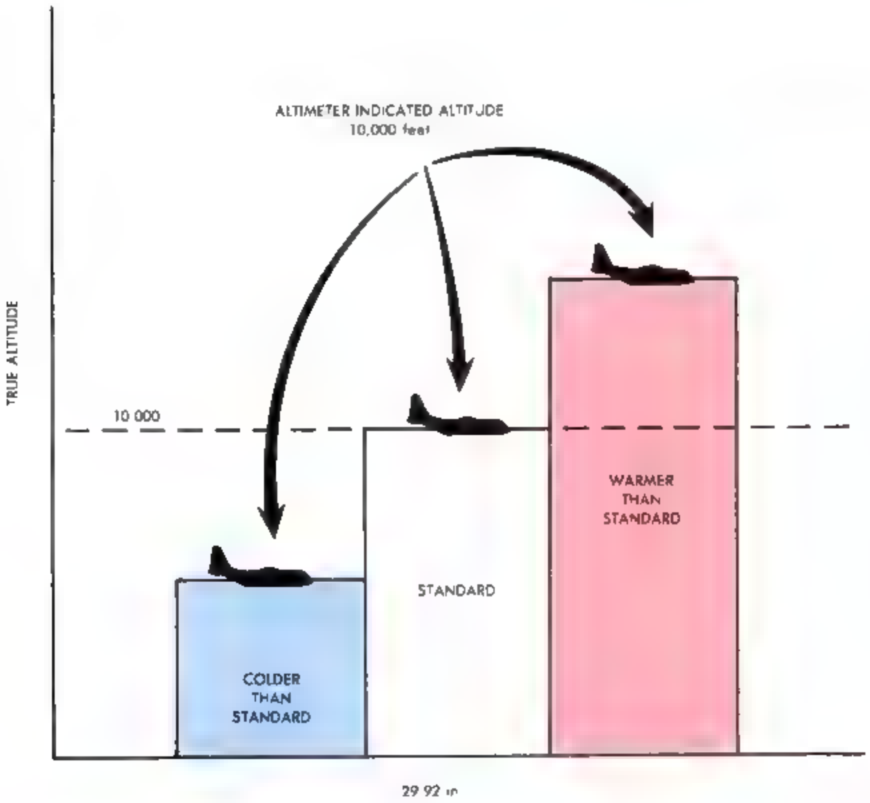


Figure 4-10. Effect of Temperature on True Altitude.

QNE Altimeter Setting. QNE is always 29.92" Hg and results in the altimeter indicating height above the standard datum plane or *pressure altitude*. This altimeter setting is used above the transition altitude (18,000 feet MSL in the U.S.).

QNH Altimeter Setting The standard QNH altimeter setting is obtained by measuring the existing surface pressure and converting it to a pressure that would theoretically exist at sea level at that point. When QNH is set, the altimeter indicates height above mean sea level. This QNH altimeter setting is standard throughout most of the world

QFE Altimeter Setting. A QFE altimeter setting (used by a few nations) is the actual surface pressure and is not corrected to sea level. When QFE is set, the altimeter indicates actual elevation above the field.

An altimeter correctly set is good for aircraft traffic separation because any atmospheric pressure or temperature deviation is common to all aircraft in the area. It is also useful for landing since a ground-level pressure variation would diminish to zero. *But, the pressure altimeter will not automatically show exact height when in flight.* It is still the aircrew's responsibility to ensure terrain avoidance.

Altimetry Errors

There are three factors that determine indications of the pressure altimeter:

- The atmospheric pressure level which the instrument is measuring
- The mechanical displacement of the indicator needles - the altimeter setting.
- Instrument error. (Determined for each individual altimeter.)

Aside from the possible instrument error, it is easy to anticipate the effects of the other two variables by understanding the meteorological factors: first, the variation of sea level *pressure* from that assumed in the standard atmosphere, and second, the deviation of the vertical *temperature* distribution from that assumed in the standard atmosphere

Pressure Error

At and above the transition altitude (18,000 feet MSL in the U.S.), aircraft altimeters must be set to the standard altimeter setting 29.92 inches Hg (figure 4-11). The pilot flying above the transition level must adjust the altimeter to the QNH setting when descending through the transition level for operation below that altitude. This will provide proper air traffic and terrain separation. When flying below the transition altitude, the altimeter should be adjusted to the surface pressure setting (QNH) setting of the nearest ground reporting station. Figure 4-12 shows the dangerous situation the aircrew may encounter if the altimeter is not adjusted in flight. Note that in flying from high pressure to lower pressure without adjusting the altimeter, the aircraft is losing true altitude. *Remember that a one-inch change in the altimeter will result in a change of about 1,000 feet in indicated altitude.*

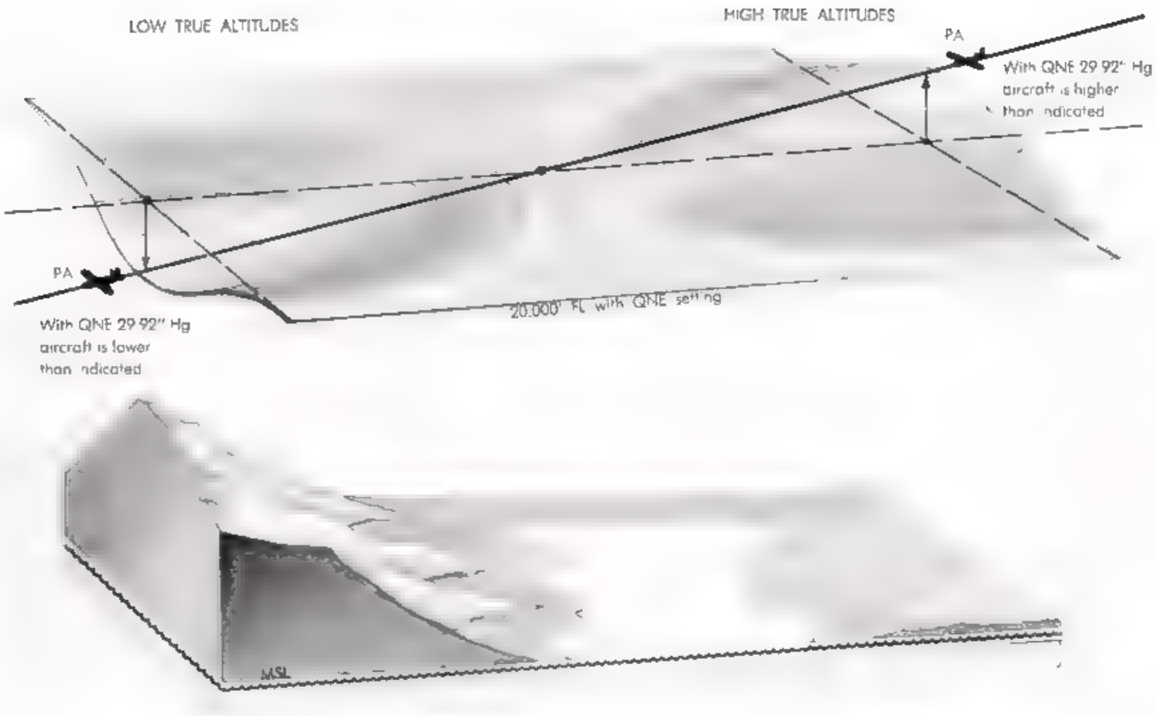

LOW TRUE ALTITUDES
HIGH TRUE ALTITUDES
PA
With QNE 29.92" Hg aircraft is higher than indicated
PA
With QNE 29.92" Hg aircraft is lower than indicated
20,000' FL with QNE setting
MSL

Figure 4-11. Flight Level Is Surface Of Constant Atmospheric Pressure Aloft, Independent of Surface Pressure Variations.

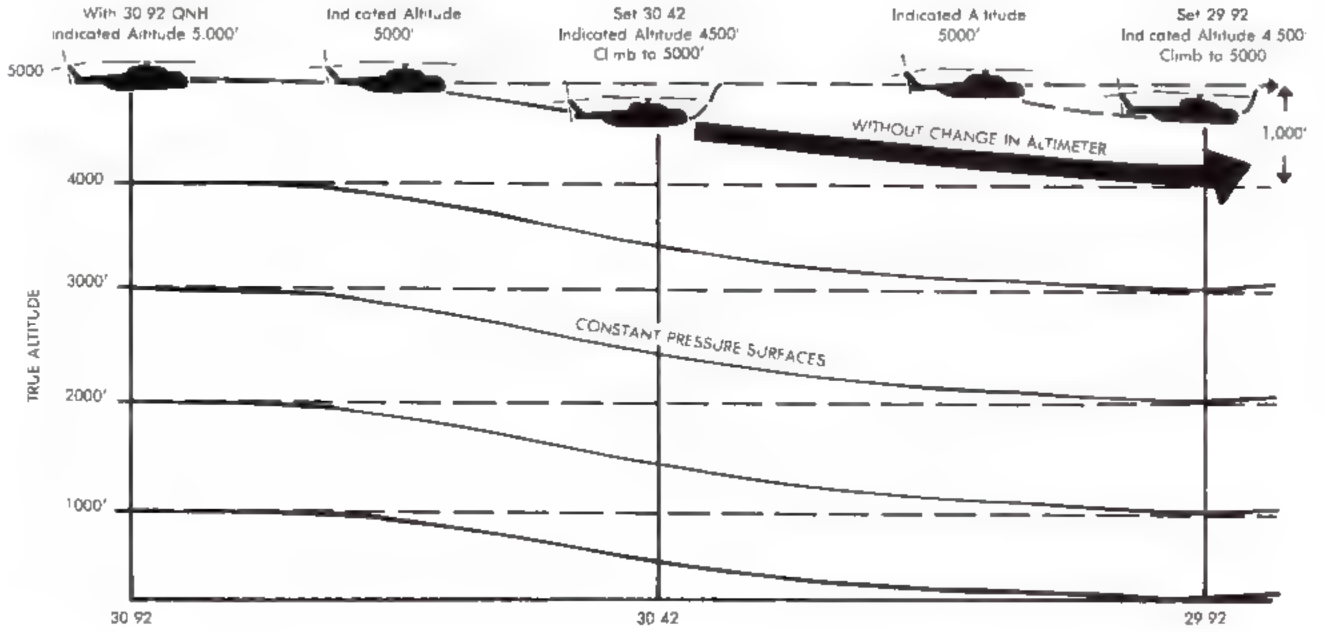

With 30.92 QNH indicated Altitude 5,000'
Indicated Altitude 5000'
Set 30.42 Indicated Altitude 4500' Climb to 5000'
Indicated Altitude 5000'
Set 29.92 Indicated Altitude 4,500' Climb to 5000
WITHOUT CHANGE IN ALTIMETER
1,000'
5000
4000
3000'
2000'
1000'
TRUE ALTITUDE
CONSTANT PRESSURE SURFACES
30.92
30.42
29.92

Figure 4-12. True Altitude Error Due To Changes In Surface Pressure Altimeter Setting.

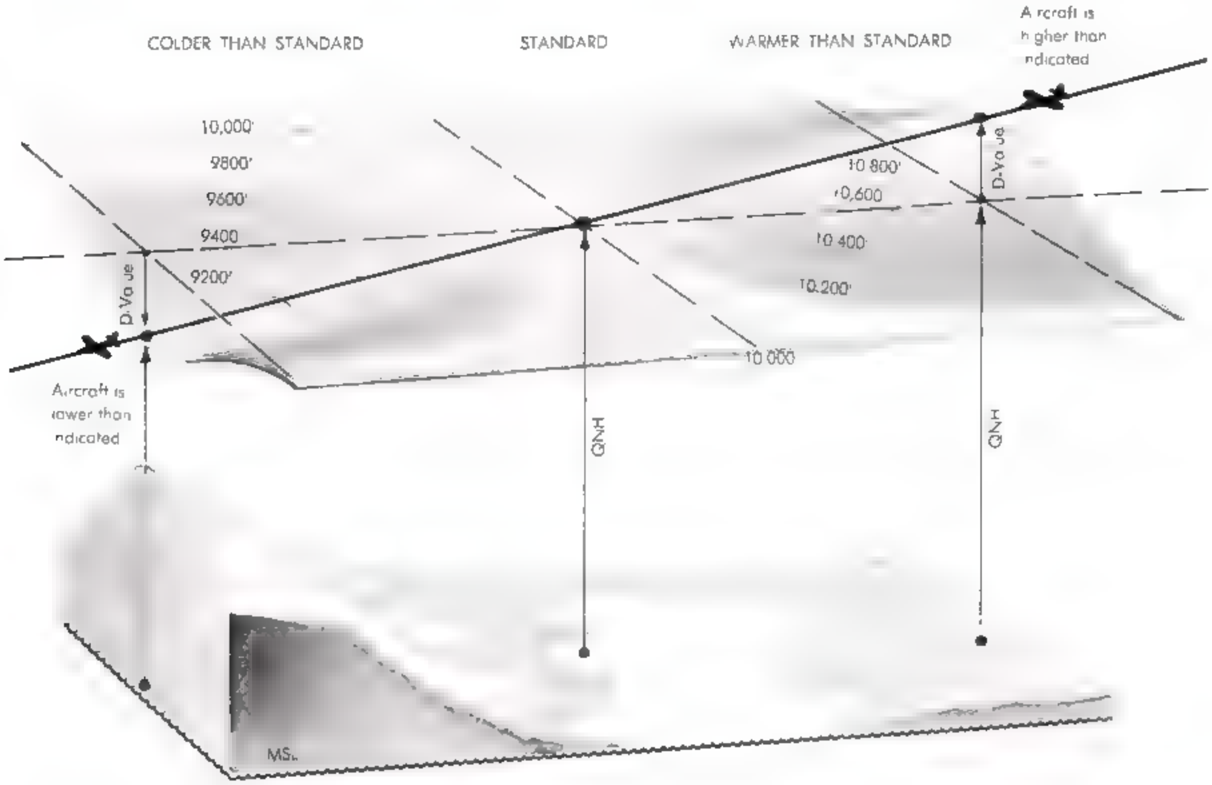


Figure 4-13. True Altitude Error Due To Nonstandard Temperatures Aloft (D-Value).

Temperature Error

Even when sea level pressure does not change along a route of flight, incorrect altitude indications may result from temperature changes. If the air is colder than the standard atmosphere, the aircraft will be lower than the altimeter indicates; if the air is warmer, the aircraft will be higher than the altimeter indicates (figure 4-13) It is important that crew members understand these errors so that when flying in cold weather and operating in mountainous regions at minimum enroute altitudes (MEA), they do not have difficulty maintaining terrain clearance.

Density Altitude

Density altitude is defined as the altitude at which a given density is found in the standard atmosphere Since standard atmospheric conditions are seldom encountered, the density altitude for an airfield may vary several thousand feet from the actual mean sea level elevation of the field

On a hot day, the air becomes "thinner" and its density at the field is equivalent to a higher altitude in the standard atmosphere. The field then has a high (+) density altitude. An example of this would be a field located 5,000 feet above mean sea level with a density altitude of 10,000 feet (figure 4-14). An aircraft flying at this field would then be operating in air normally found in the standard atmosphere at 10,000 feet. Conversely, on a cold day the air becomes heavy. Its density is the same as that at an altitude in the standard atmosphere lower than the field elevation. The density altitude is then lower (-) than normal

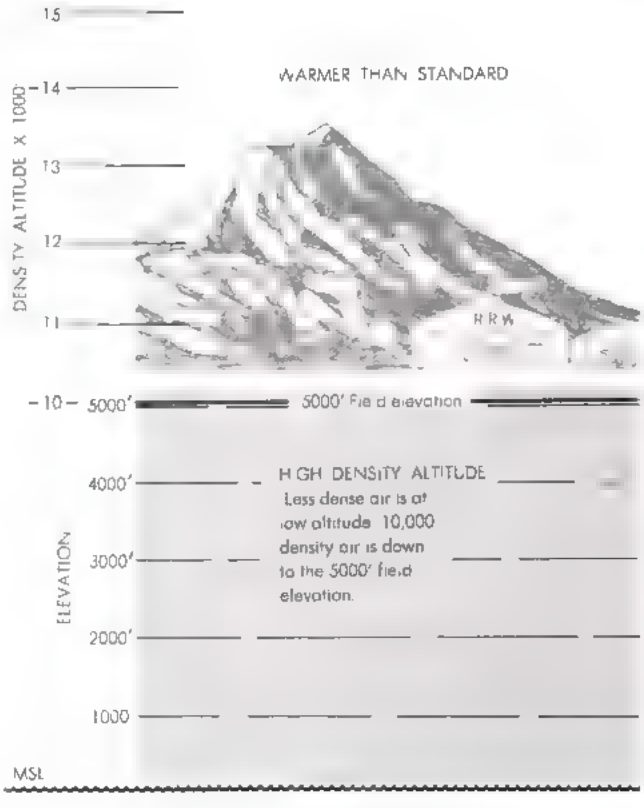


Figure 4-14. Density Altitude.

The efficiency of aircraft performance is greatly affected by the varying densities of the atmosphere. Low density altitude increases aircraft performance. High density altitude, however, can be a hazard since it reduces aircraft performance, especially if the aircraft is critically loaded. The lift of the wing or blade is affected by the speed of the air around it and the density of the air through which it moves. In areas of high density altitude, additional engine power is required to compensate for the thin air. Takeoff and landing rolls are lengthened, and rates of climb and service ceiling are reduced.

Temperature variation is incorporated into a formula for obtaining density altitude from a known pressure altitude. Each 1°C variation from standard temperature changes the density altitude approximately 120 feet. If the actual temperature is below standard, the density altitude is lowered.

DA = PA + (120 x Vt) where:
DA is density altitude
PA is pressure altitude
120 is the temperature constant (120 feet per 1°C)
Vt is the variation of the actual air temperature from standard at the pressure altitude.

Example.

The field elevation is 1,500 feet with a current altimeter setting of 29.41. Surface temperature is 30°C.
Pressure altitude variation (PAV) = (29.92 - 29.41) x 1,000 = 510 feet
PA = field elevation + PAV = 1,500 + 510 = 2,010 feet
The standard temperature for 2,010 feet is 11°C
Vt = 30°C - 11°C = 19°C
DA = 2,010′ + (120 x 19) = 4,290 feet

Density altitude can also be determined by using a dead reckoning (DR) computer.

CHAPTER 5

WIND

Atmospheric pressure and temperature variations cause the air to move in two ways: ascending and descending currents and the horizontal flow of air known as wind. Both of these air motions are of primary interest to the aircrew because they affect the flight of aircraft and bring about changes in weather which may make a difference between a safe flight and disaster Wind transports water vapor and therefore plays an important role in the formation of fog and clouds and on the production of precipitation.

This chapter deals mostly with the *horizontal* flow of air. The movement of air in ascending and descending currents is treated in subsequent chapters of this manual

GENERAL CIRCULATION

The term *circulation* may be considered as simply the movement of air relative to the earth's surface. Since the atmosphere is fixed to the earth by gravity and rotates with the earth, there would be no circulation were it not for forces which upset the atmosphere's equilibrium.

The sun heats the earth's surface unevenly. The most direct rays of the sun strike the earth in the vicinity of the equator, thus heating equatorial regions much more than the polar regions. In addition, equatorial regions re-radiate less heat to space than is received from the sun while the reverse is true at the poles. Yet, the equatorial regions do not continue to get hotter and hotter, nor the polar regions colder and colder The only plausible explanation is that heat is transported from one latitude to another by the actual circulation

Hypothetical Circulation System

Let's set up a hypothetical situation to illustrate what is generally considered as the basic *cause* of air movement. Imagine the earth in a stationary position - without orbit or rotation - with the *sun revolving* around it at its equator. Furthermore, assume that the earth was devoid of all topographical features that would affect normal local wind flow and that the earth's surface was uniform with respect to its heat capacity. With the stage set, let's look at the basic air movement as shown in figure 5-1.

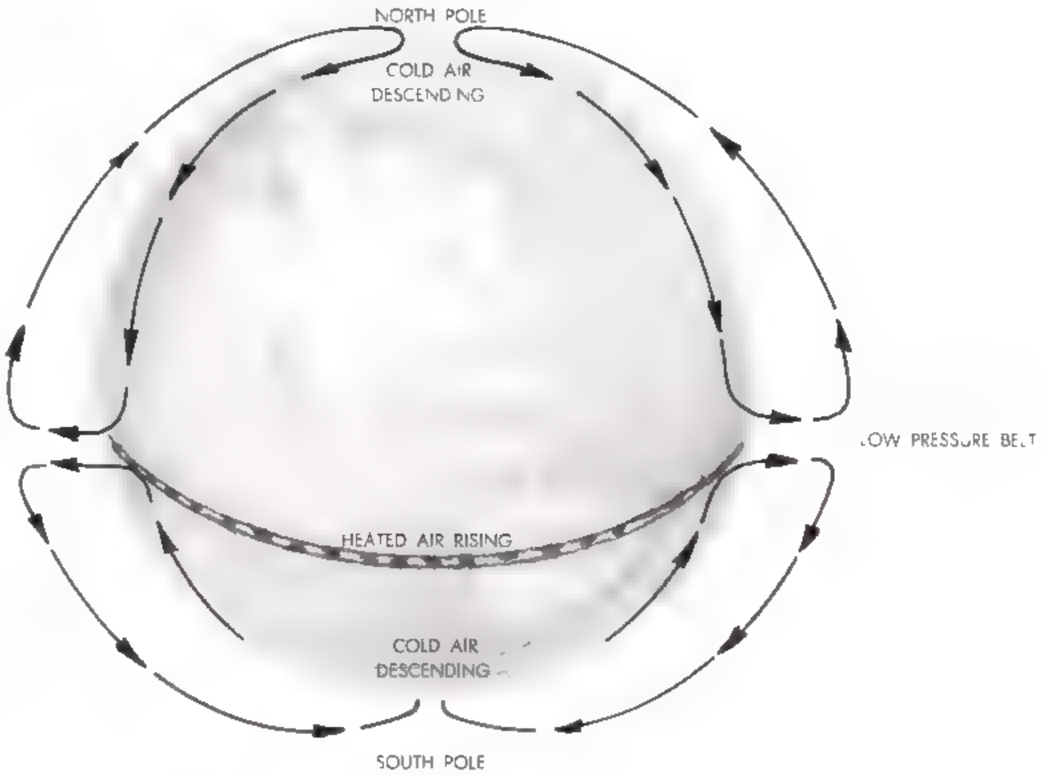


Figure 5-1. Theoretical Basic Air Movement.

Surface winds would have their origin at the polar regions and would flow toward the equator. As these winds flowed toward the equator, they would become exposed to more and more terrestrial radiation which heats the air. As the air was heated, it would expand, becoming less dense. This lighter air would rise, reaching its apex at the equator - the spot of maximum insolation. The two hemispheric surface winds would now meet and begin to turn back towards their respective poles, flowing through the upper regions. As this air retreated from the equatorial region it would be cooled, becoming more dense until it would once again descend to the surface near the poles, ready to repeat its hemispheric journey.

Under such a hypothetical situation, all surface winds in the Northern Hemisphere would flow directly from the north to the south, and all surface winds in the Southern Hemisphere would flow from the south to the north. Furthermore, the lows and highs would be simple to record The cold, dense descending air at the poles would exert more surface pressure, pushing the mercury up higher in the barometric tube to record our highs. The hot, less dense ascending air at the equator would produce just the opposite effect for our lows. In reality, our *basic circulation system* is much the same.

The massive energy necessary to continue this basic circulation system comes from our sun. Without it our atmosphere would not move. Since most of this energy (heat) is directed at the equator, it is here that we can pinpoint the start of the circulation system cycle. This heat evacuates the air from the equator into the upper regions of the troposphere. This makes room for the colder, more dense air from the "highs" - emanating from the polar regions - to flow into this "low" (the equatorial region) in much the same way that water flows from high to low places.

Factors Influencing Actual Circulation

Because the earth *does* rotate and its surface is not *even* and *uniform* in heat capacity, we must examine the more important ways in which the simple circulation pattern in figure 5-1 is modified. This circulation is modified considerably by

- the irregular distribution of *oceans and continents*,
- the relative effectiveness of differing surfaces in transferring heat to the atmosphere,
- *irregular terrain*,
- the *daily variation in temperature*,
- the *seasonal changes*, and many other factors.

These factors lead to the establishment of semipermanent regions of high and low pressure which control the general atmospheric movements in their regions Refer to figure 5-2 for the normal positions in January and July of these principal high and low pressure areas

The semipermanent highs and lows are important to our basic understanding of the atmosphere's circulation and to the pilot or navigator in day-to-day flight planning. However, of far greater significance are the moving lows (migrating cyclones) and highs (migrating anticyclones) which are associated with the rapid changes in weather so characteristic of the middle latitudes.

WIND DIRECTION

These migrating air masses are the sources of our surface winds - but not necessarily their *direction*. In some cases where the flow of high pressure systems (colder, denser air masses) displaces warmer, less dense air masses (lows), and the distance is comparatively short, that air flow can be direct.

However, as the distance lengthens, other forces that affect the direction of wind come into play. These forces include Coriolis force, pressure gradient force, friction, and gravity. For brevity, we will describe all activity as it occurs in the Northern Hemisphere, remembering that these forces affect wind direction just the opposite in the Southern Hemisphere.

CORIOLIS FORCE

The earth rotates from west to east at a given speed in much the same way that a phonograph record turns on a turntable. Although the revolutions-per-minute (RPM) are the same, the outward rim of the phonograph record (which in the case of the earth is the equator) has more distance to cover over one complete revolution than any of the inner points of the record (which would be comparable to the higher latitudes on earth) and is therefore traveling at a faster rate of speed. Our atmosphere is brought along by its gravitational attachment to earth at the same relative speeds at each latitude. However, when a migrating pocket of air moves toward another latitude - either northward or southward - a phenomenon takes place known as the *Coriolis force* (figure 5-3). If the pocket of air moves northward from a lower latitude to a higher latitude, it will move ahead (to the right) of the point directly north of its initial starting point because of its greater speed.

Similarly, a pocket of air moving from north to south, from an area with a smaller circumference to an area with a larger one, would encounter a lag because it is entering a plane with a greater rim speed than the plane it left. Therefore, because of the lag, it too would encounter the effect of a deflection to the right.

From this we can see that while the only force at work is the rotation of the earth, pockets of air moving north or south over considerable distances are deflected to the right in the Northern Hemisphere (figure 5-4). Therefore, if a pocket of air should migrate from north to south, the wind at the surface would be *from* the east. (Wind direction is always expressed as being the direction from which it comes)

Other Deflective Forces

Two other elements produce similar wind deflections, the origins of which are of an east-west nature The rotation of the earth produces a centrifugal force, the greatest of which is felt at the equator. The other element is true gravity, which is felt strongest at the poles because there is less influence from centrifugal force.

These two forces, gravity and centrifugal force, tend to neutralize each other as long as the speed of the rotation of the earth is maintained. Without centrifugal force, free-moving bodies on the earth would be drawn toward

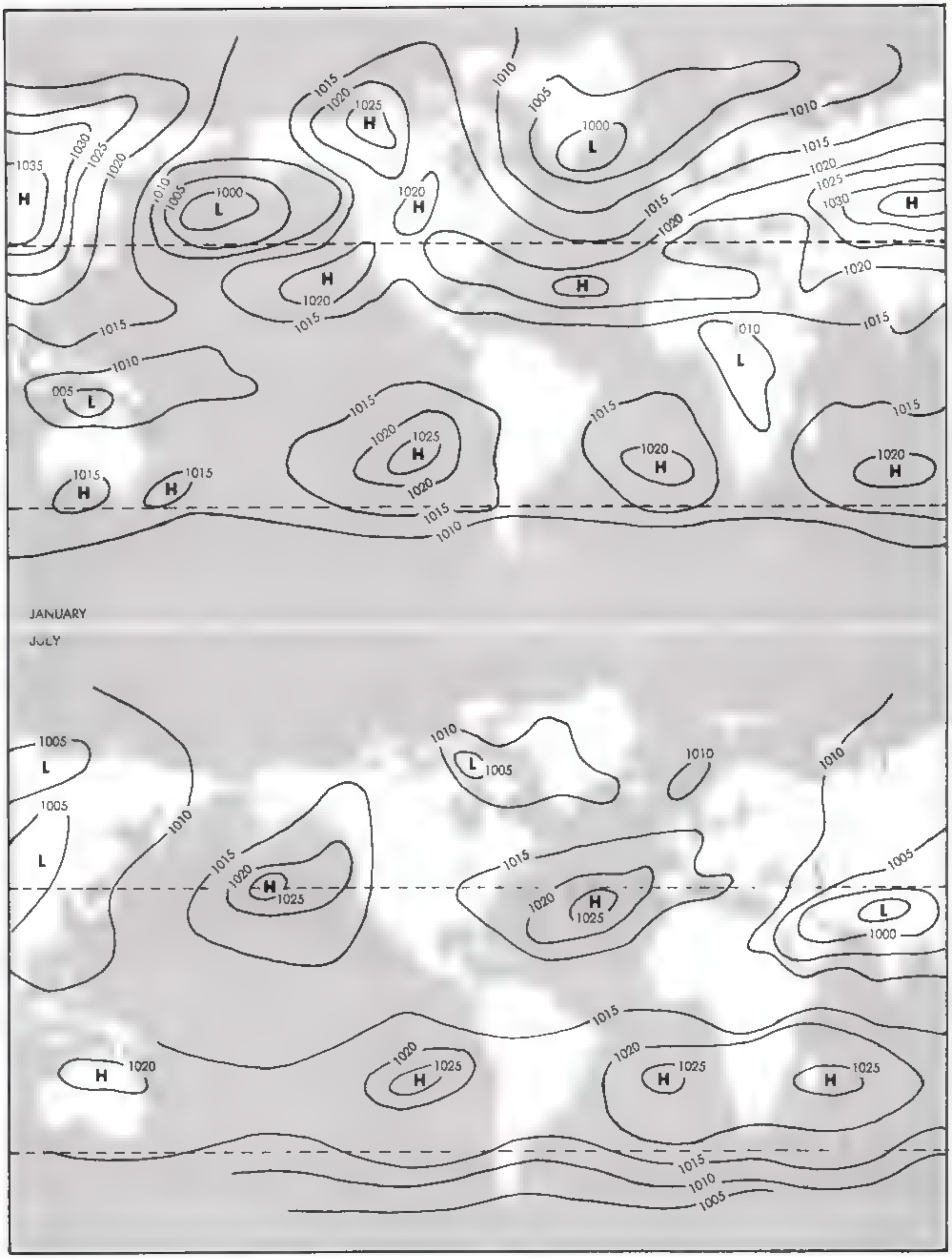
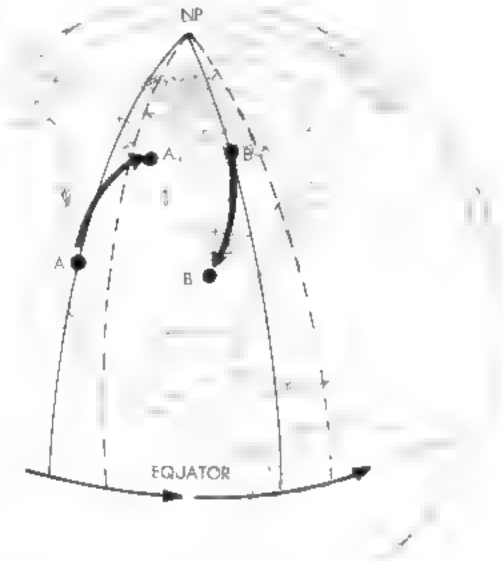


Figure 5-2. Worldwide Surface Pressure Distribution.



As point A tracks north, its original eastward velocity starts exceeding the surface speed and gets ahead of its starting meridian. The effect is a curved track to the right point A'

As point B tracks south, its original eastward velocity becomes less than the surface speed and gets behind its starting meridian. The effect is a curved track to the right, point B

Figure 5-3. Coriolis Force.

the poles. By the same token, without gravity's poleward component, free bodies would be drawn toward the equator through centrifugal force. Therefore, the conclusion is that the speed of a moving body traveling from west to east (along with the rotation of the earth) would add to the rotational speed of the earth resulting in an *increase* in centrifugal force. This would draw that body, in this case a pocket of air, toward the equator (to the right in the Northern Hemisphere). A free-moving body moving in the opposite direction (from east to west against the rotation of the earth) would subtract from the speed of the rotation of the earth, lessening the effects of centrifugal force and turning that body toward the pole - or to the right in the Northern Hemisphere. Notice now that all deflective motion is approximately 90 degrees to the right of its source of origin in the Northern Hemisphere and to the left in the Southern Hemisphere.

The Coriolis force is strongest at the poles and decreases to zero at the equator. The stronger the wind, the stronger is this deflective force.

Pattern of Circulation

We will now apply Coriolis force to the simplified pattern of circulation (figure 5-5A). For brevity, we will again confine movement to the Northern Hemisphere. As the air is forced to rise (figure 5-5B) and moves northward from the equator, it is deflected toward the east. By the time it has traveled about a third of the distance to the pole, it is no longer moving northward, but eastward. This causes the air to pile up in the so-called "horse latitudes" (around 30° north latitude) and produces a high pressure area. Air at the surface moving southward out of the horse latitudes is deflected toward the west, producing the *northeast trade winds.*

In the polar regions, a similar process is in operation, with the southward-moving polar air being deflected toward the west to become an east wind. Air forced northward from the high pressure area near 30° latitude is deflected toward the east to be come a west wind, thereby producing the *prevailing westerlies* of the middle latitudes. When this air meets the colder polar air, it moves up over the colder air, producing an accumulation of air in the upper latitudes. The cold air is spasmodically forced to break out from under this accumulation in waves which surge toward the equator, reducing the accumulated pressure. This is called a polar outbreak or cold wave. The boundary zone in which the wedge of cold polar air and the warmer air of the prevailing westerlies come in to play is called the *polar front.*

PRESSURE GRADIENT FORCE

In the Northern Hemisphere, the air flows clockwise around a high pressure area and counterclockwise around an area of low pressure This movement is often referred to as cyclonic for low pressure areas and anticyclonic for high pressure areas.

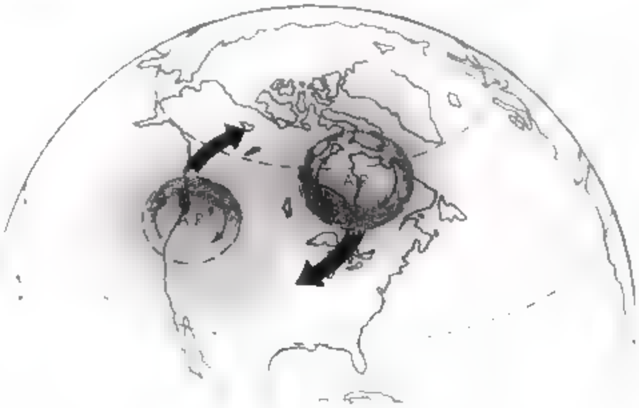


Figure 5-4. Coriolis Force Affects Circulation Patterns.

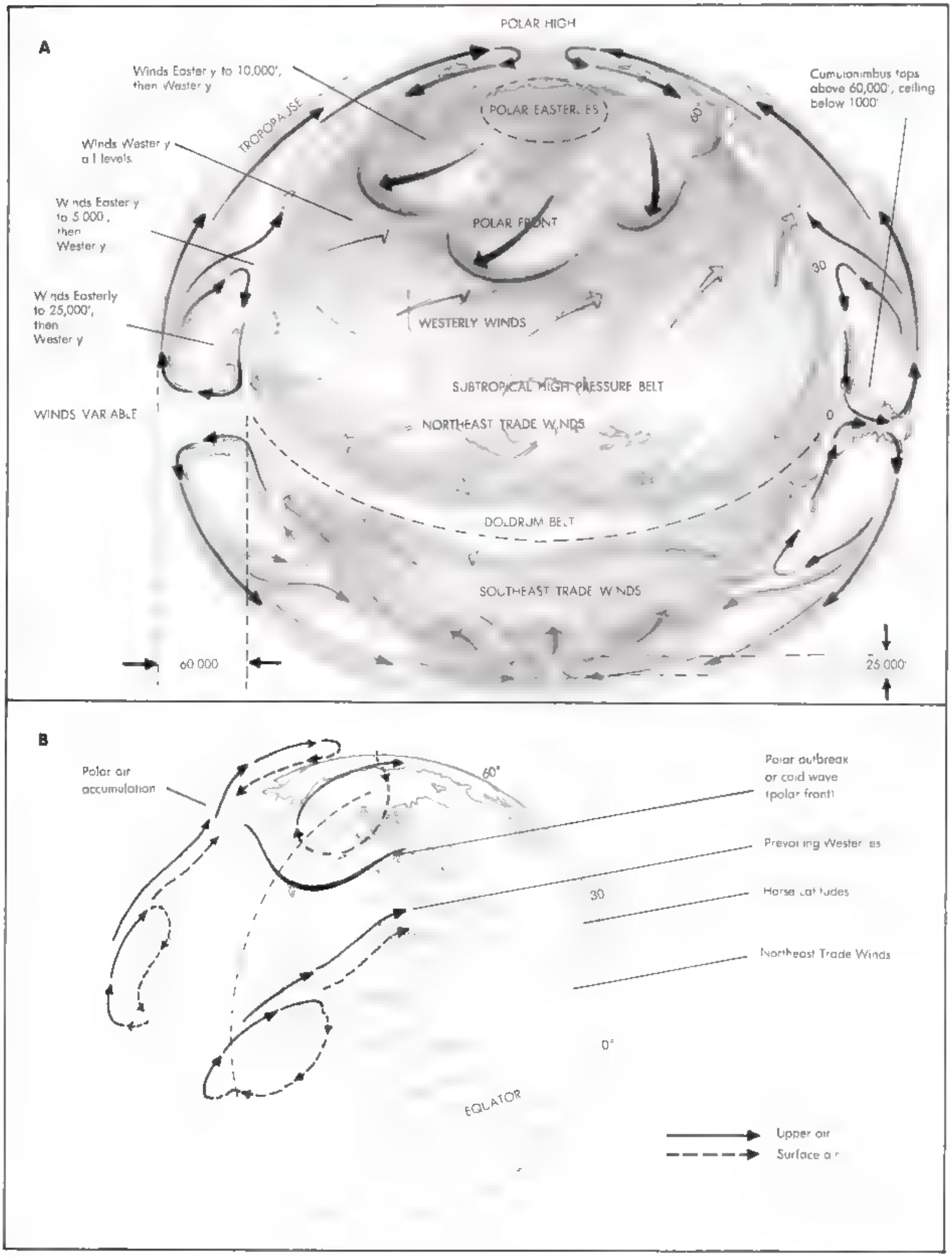

A
POLAR HIGH
Winds Easterly to 10,000', then Westerly
Cumulonimbus tops above 60,000', ceiling below 1000'
TROPOPAUSE
POLAR EASTERLIES
60°
Winds Westerly all levels
Winds Easterly to 5,000', then Westerly
POLAR FRONT
30
Winds Easterly to 25,000', then Westerly
WESTERLY WINDS
SUBTROPICAL HIGH PRESSURE BELT
WINDS VARIABLE
0
NORTHEAST TRADE WINDS
DOLDRUM BELT
SOUTHEAST TRADE WINDS
60,000
25,000'
B
Polar air accumulation
60°
Polar outbreak or cold wave (polar front)
Prevailing Westerlies
30
Horse Latitudes
Northeast Trade Winds
0°
EQUATOR
Upper air
Surface air

Figure 5-5. Patterns Of Atmospheric Circulation.

The rate of change with *horizontal* distance between these higher and lower pressure areas is called *pressure gradient* The greater the difference in pressure between two horizontal points, the greater is the pressure gradient between those points. This greater difference in pressure is indicated on surface and upper air charts by a closer spacing of the isobars and contours respectively and further indicates higher wind speeds.

The reason for this begins when a pocket of air from the higher pressure area, in following a tendency for air to flow directly from high to low areas, starts to move toward the low pressure area (figure 5-6A). As it does, Coriolis force begins to swing the pocket of air to the right. The force that initiated the horizontal movement (pressure gradient) still exerts its pull which is now to the left. When the air is blowing parallel to the isobars or contours, the Coriolis force is just balanced by the pressure gradient. As this pocket of air enters these "lanes" between isobars or contours, it is virtually squeezed through the more narrow channels formed by greater pressure gradient, and shown on the surface chart by a closer spacing of the isobars (figure 5-6B) Thus the moving pocket of air, channeled into a more narrow corridor, will pick up speed. If it enters an area in which the isobars indicate less pressure gradient (by being spaced farther apart), the wind will lose speed.

Note that without Coriolis force, the pocket of air would move directly across the isobars from the high to the lower pressure area until the pressure was equalized in much the same way that water seeks its own level. It is this attempt to equalize pressure that initiates the movement of the pocket of air from the higher to the lower pressure area. As air is evacuated from the low, an equalizing pocket of air is drawn from the high pressure area to take its place.

EFFECTS OF FRICTION AND GRAVITY

Surface friction tends to retard air movement Since the Coriolis force varies with the speed of the wind, a reduction in the wind speed by friction means a reduction in the Coriolis force. This results in a momentary disruption of the balance between Coriolis force and pressure gradient force. When the new balance, including friction, is reached, the air blows at an angle across the isobars from high pressure to low pressure. This angle varies from 10° over the oceans to as much as 45° over rugged terrain. Frictional effects on the air are greatest near the ground, but the effects are also carried aloft by ascending currents. Surface friction is effective in slowing down the wind up to about 1,500 to 2,000 feet above the ground (figure 5-7). Above this level, the effect of friction decreases rapidly and may be considered negligible for all practical purposes. Therefore, air about 2,000 feet or more above the ground usually tends to flow parallel to the isobars and contours. Figure 5-8 illustrates the flow of air around high and low pressure areas above the surface frictional layer.

The force of gravity pulls the air downward and produces a vertical density distribution so that the more dense (heavier) air lies below less dense (lighter) air.

LARGE WIND SYSTEMS

Persons living in the temperate zone and farther north know that their weather is changing almost constantly with the alternate passage of cyclones (low pressure systems) and anticyclones (high pressure systems). These migrating systems, on the average, move from west to east with the prevailing westerly winds They are accompanied by wind shifts and, with some exceptions, large and rapid changes in temperature and broad moving areas of precipitation. Migrating cyclones and anticyclones furnish the most important means through which heat is exchanged between high and low latitudes (figure 5-9).

Cyclones and Anticyclones

Cyclones (lows) are usually a few hundred miles in diameter. Anticyclones (highs) are generally larger and often more elongated, the longer axis extending for 2,000 miles or more in some cases (figure 5-10).

Hurricanes and Typhoons

Hurricanes originate over the Atlantic Ocean, the Caribbean Sea, the Gulf of Mexico, and the eastern Pacific along the coasts of Central America and Mexico In the tropical areas of the western Pacific Ocean, they are called typhoons.

The extremely low pressure, very strong winds, torrential rains, and other characteristics of the hurricane or typhoon make them adaptable for discussion in several chapters of this manual. Their treatment in detail is reserved for Chapter 15, Tropical Weather, since these phenomena are born in the tropics.

Jet Streams

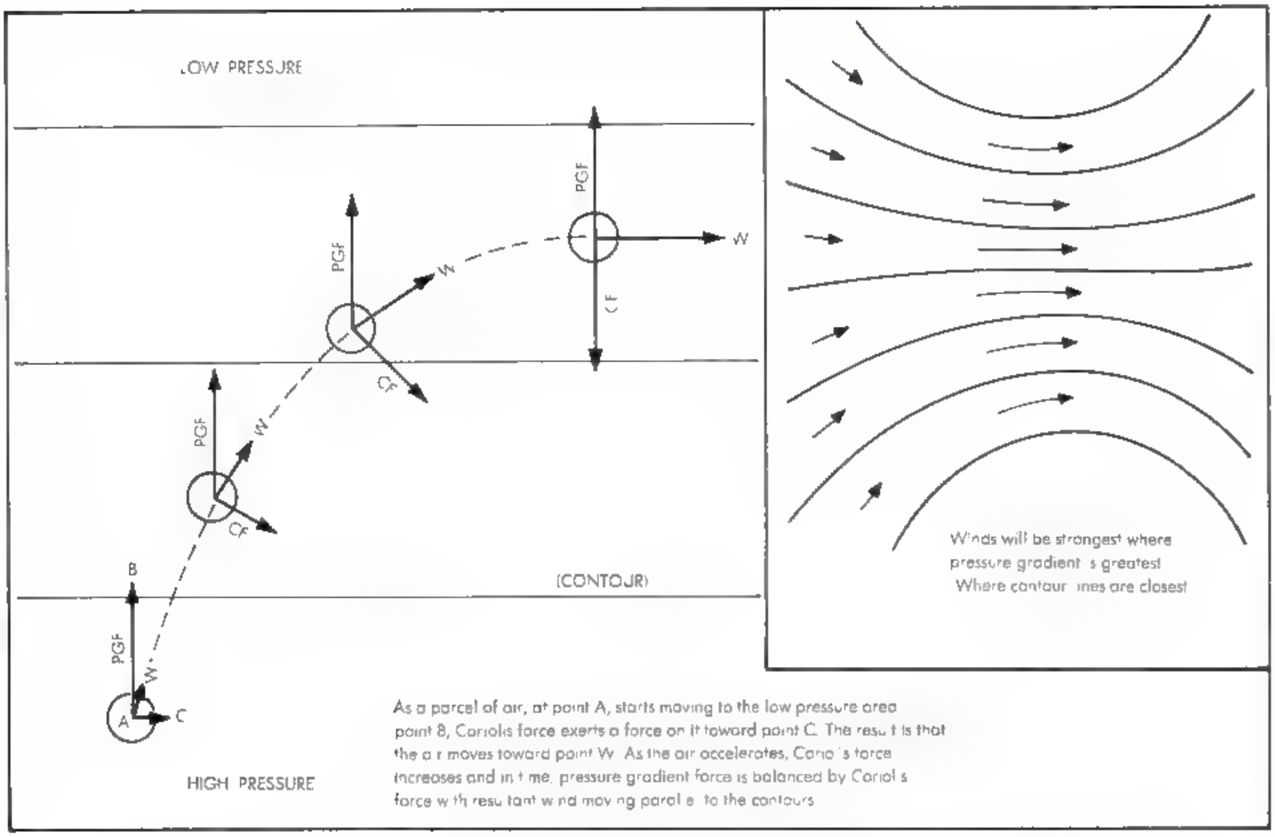
A discussion of large scale wind systems is incomplete without some mention of the "jet stream." Winds on the average increase with height through the troposphere, reaching a maximum near the level of the tropopause. The maximum winds tend to be further concentrated in narrow bands The jet stream, then, is a narrow band of strong winds meandering through the atmosphere at a level near the tropopause. It is discussed in more detail in Chapter 10

LOCAL WINDS

Superimposed on the general wind systems are local wind systems created by mountains, valleys, and water masses. These local systems usually cause significant changes in the weather of the area. The term "local," in the case of wind systems, applies to areas whose sizes range from about one-half of an average size state to roughly the size of two average states.

Land and Sea Breezes

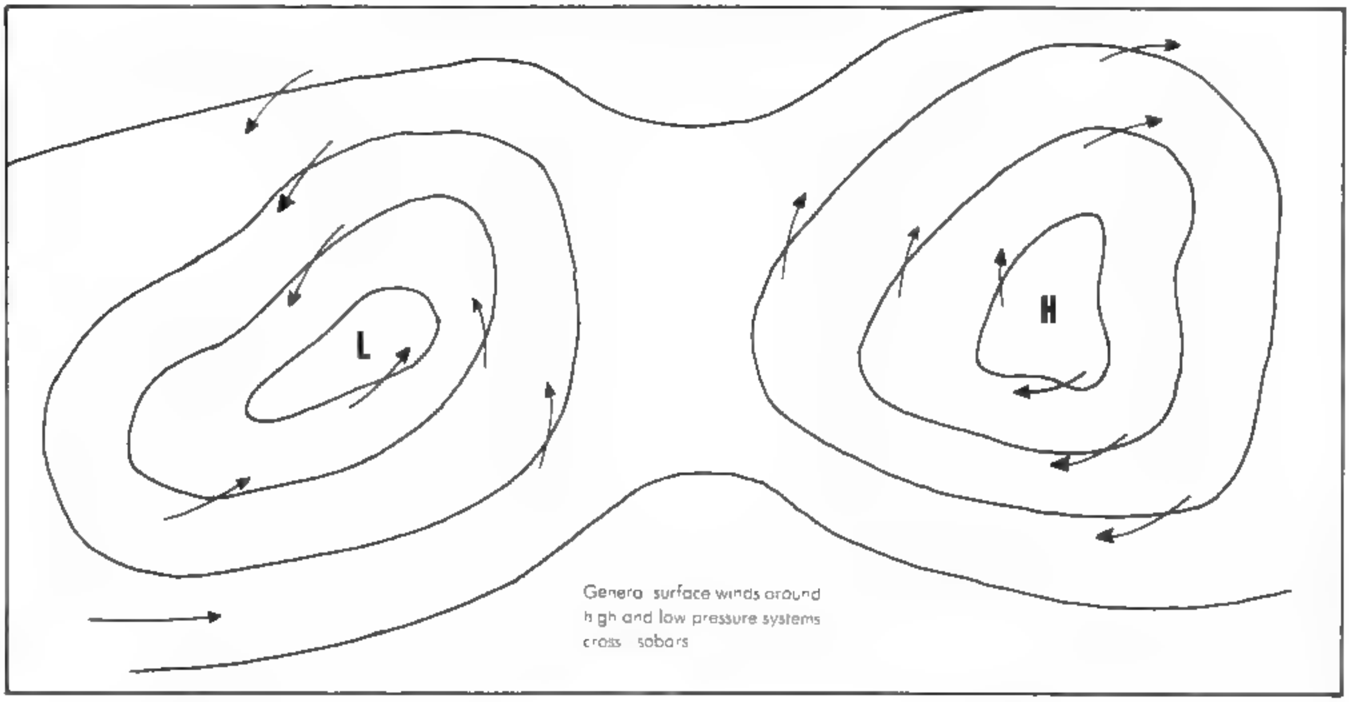
Land surfaces warm and cool more rapidly than water surfaces through insolation and terrestrial radiation Therefore, the land is normally warmer than the sea during the day and colder at night. This difference in temperature is more noticeable during the summer months and when there is little horizontal transport of air in the low levels. In coastal areas, this difference of



Winds will be strongest where pressure gradient is greatest. Where contour lines are closest

As a parcel of air, at point A, starts moving to the low pressure area point B, Coriolis force exerts a force on it toward point C. The result is that the air moves toward point W. As the air accelerates, Coriolis force increases and in time, pressure gradient force is balanced by Coriolis force with resultant wind moving parallel to the contours.

Figure 5-6. Effect of Pressure Gradient and Coriolis Force On Wind Direction.



General surface winds around high and low pressure systems cross isobars

Figure 5-7. Surface Winds Are Deflected Across Isobars Toward Lower Pressure.

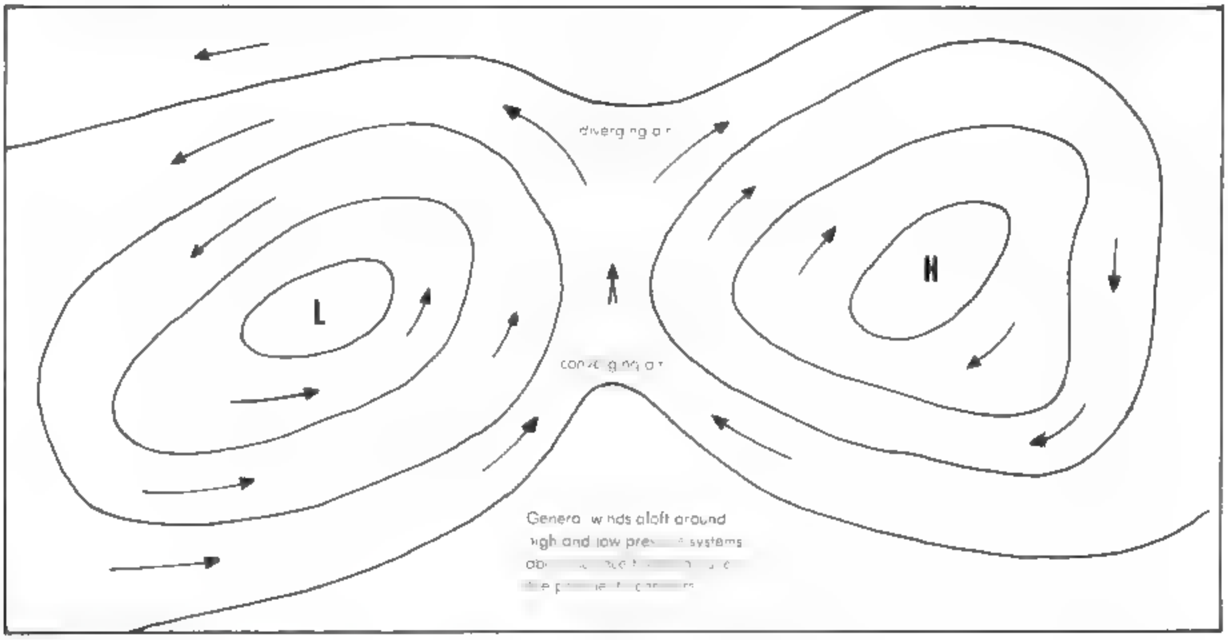


Figure 5-8. Wind Direction Around Contours (Aloft).

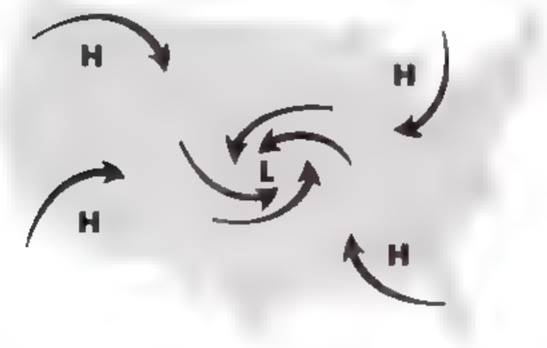


Figure 5-9. Air Flow Aids In Exchange Of Heat Between Latitudes.

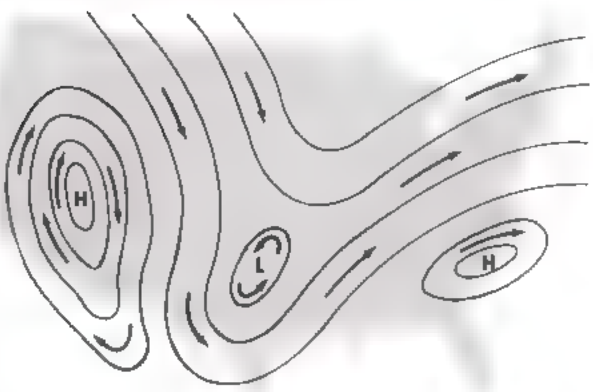


Figure 5-10. Large High Pressure System (Anticyclone).

temperature between the land and water produces a corresponding difference in pressure (pressure gradient) During the day, the pressure over the warm land becomes lower than that over the colder water. The cool air over the water moves toward the lower pressure, forcing the warm air over land upward The resulting onshore wind is called a "sea breeze"

At night the circulation is reversed so that the air movement is from land to sea, producing an offshore wind called the "land breeze." The sea breezes are usually stronger than the land breezes, but they seldom penetrate far inland. Both land and sea breezes (figure 5-11) are shallow in depth.

The possible existence of a land breeze (at night) or a sea breeze (during the day) should be considered during takeoff and landing near large lakes and oceans. Sea breezes of 15 to 20 knots are not uncommon.

Mountain and Valley Winds

In the daytime, air next to a mountain slope is heated by contact with the ground as the ground receives radiation from the sun. This air usually becomes warmer than air at the same altitude but farther away from the slope. Colder, more dense air in the surroundings settles downward and forces the warmer air near the ground up the mountain, producing the *valley wind*, so called because the air seems to be flowing up out of the valley (figure 5-12).

At night the air in contact with the mountain slope is cooled by outgoing terrestrial radiation and becomes more dense than the surrounding air. It sinks along the slope, producing the *mountain breeze*.

Katabatic Winds

A *katabatic wind* is any wind blowing down an incline The mountain breeze, therefore, is a type of katabatic

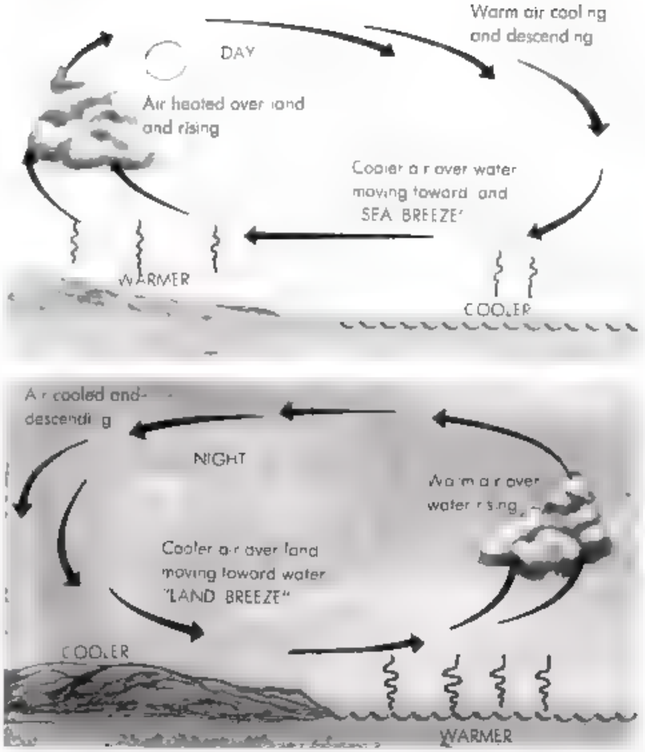

Warm air cooling and descending
DAY
Air heated over land and rising
Cooler air over water moving toward land SEA BREEZE"
WARMER
COOLER
Air cooled and descending
NIGHT
Warm air over water rising
Cooler air over land moving toward water "LAND BREEZE"
COOLER
WARMER

Figure 5-11. Land and Sea Breezes.

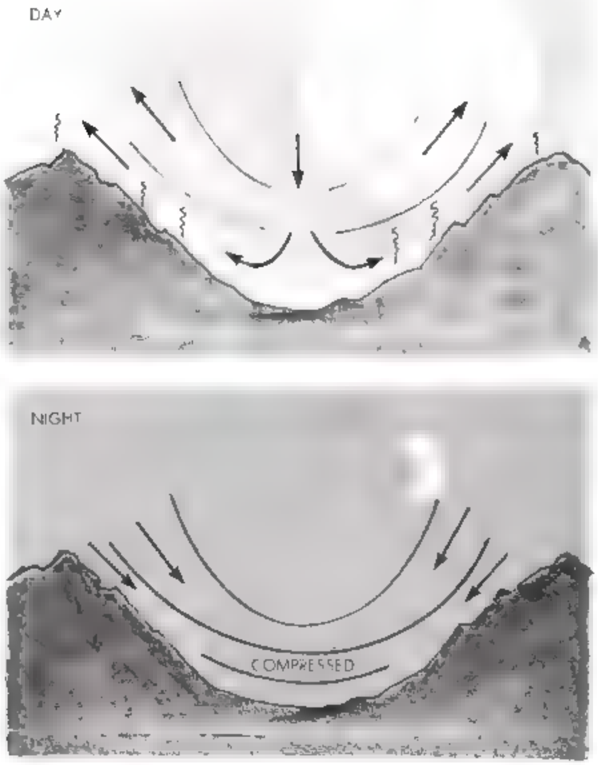


Figure 5-12. Valley Wind and Mountain Breeze.

wind. If the downslope wind is warm relative to the air in the valley or plain below, it is called a *foehn*. If the downslope wind is cold, it is called either a *fall wind* or a *gravity wind*.

Many katabatic winds recurring in local areas have been given colorful names to highlight their dramatic effect. For example, the warm wind located along the eastern slopes of the Rockies is called a *chinook* (figure 5-13). Air is heated as its moisture is condensed during the ascent on the western slopes and then is heated even more by compression as it flows downhill from the high elevations. A chinook wind can raise the temperature at the base of a mountain as much as 30°F in a few minutes Another example is the *Santa Ana*, a foehn wind descending from the Sierra Nevada Mountains into the Sanata Ana Valley of California. This warm, dry wind is noted for its very high speeds.

Fall winds are found in very cold plateau regions (figure 5-14). In southeastern Alaska the fall wind is known as the *Taku*, while in the Alps it is known as the *Bora*. Because the cold air is heavy, it flows downhill under the influence of gravity, resulting in a shallow wind which sometimes attains high speeds. These winds usually affect a rather large area and may occur either during the day or night. Fall winds are usually stronger at night though, because radiational cooling of the ground adds to the air's coldness

WIND SHEAR

If two objects are placed together and one is moved along the surface of the other, friction results. A similar process occurs between two bodies of air of differing velocities However, being fluid, one body of air will not move along the other on a plane surface. Friction will create a mixing zone of eddies between the bodies called a shear zone. Figure 5-15 shows two adjacent bodies of air moving at different velocities with their accompanying shear zone. Shear, which may be either vertical or horizontal, will be further discussed in Chapters 10 and 11.

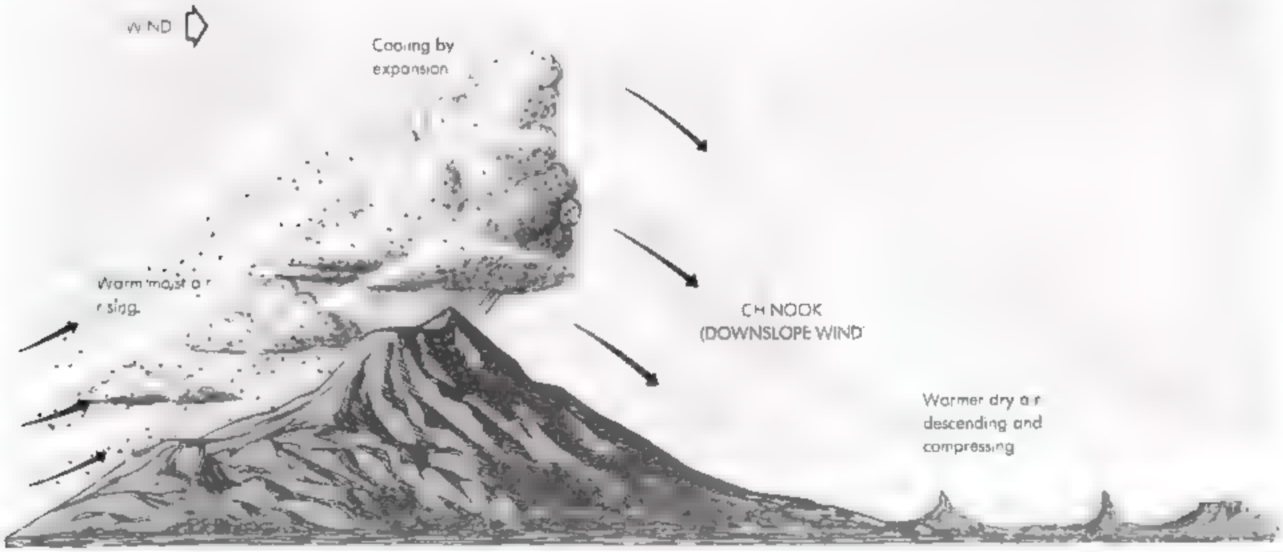


Figure 5-13. Chinook Wind.

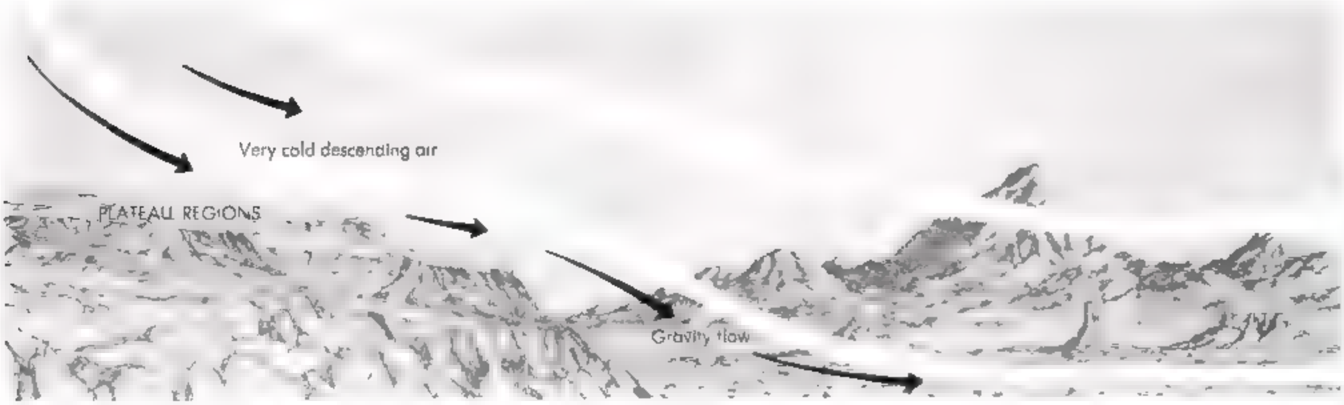


Figure 5-14. Fall Wind.

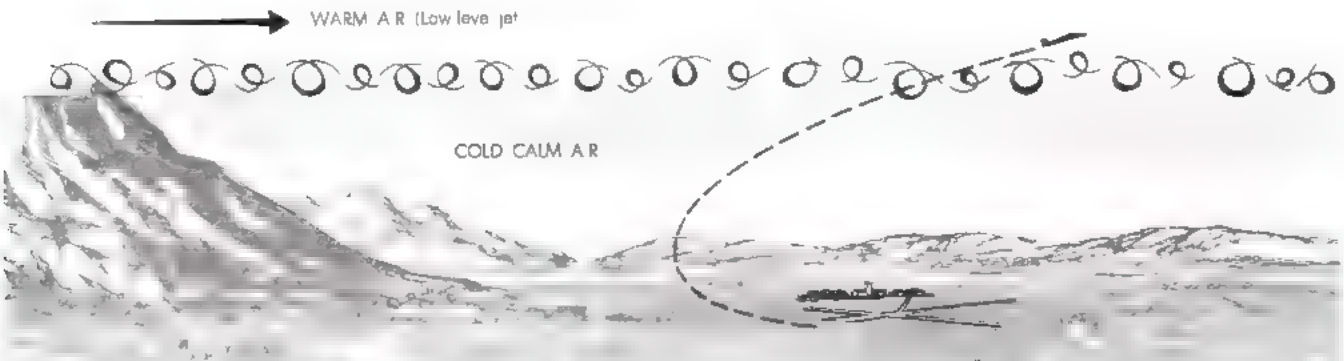

WARM AIR (Low level jet)
COLD CALM AIR

Figure 5-15. Horizontal Wind Shear Turbulence.

CHAPTER 6

STABILITY

The stability of an aircraft is a vital concern to the aircrew. A stable aircraft, if disturbed by the movement of the controls or by an external force, will return to a balanced, steady flight condition. An unstable aircraft, however, will continue to move away from the normal flight attitude.

So it is with the atmosphere. The normal flow of air tends to be horizontal. If this flow is disturbed, a stable atmosphere will resist any upward or downward displacement and will return quickly to normal horizontal flow. An unstable atmosphere, on the other hand, will allow these upward and downward disturbances to grow, resulting in turbulent air. The clearest example of such unstable development in the atmosphere is the towering thunderstorm which grows as a result of a large and intensive vertical movement of air. It climaxes in lightning, thunder, and heavy precipitation, sometimes including hail.

Stability is the atmosphere's resistance to vertical motion. It depends on the vertical distribution of the air's temperature and moisture. As shown in figure 6-1, hotter air is lighter (less dense) than colder air and moist air is lighter than dry air. Therefore, if air is warmer or more moist than its surroundings, it is unstable and it will rise. On the other hand, if the air is colder or drier than its surroundings, it is stable and it will sink until it reaches equilibrium. Figure 6-lB illustrates these relationships.

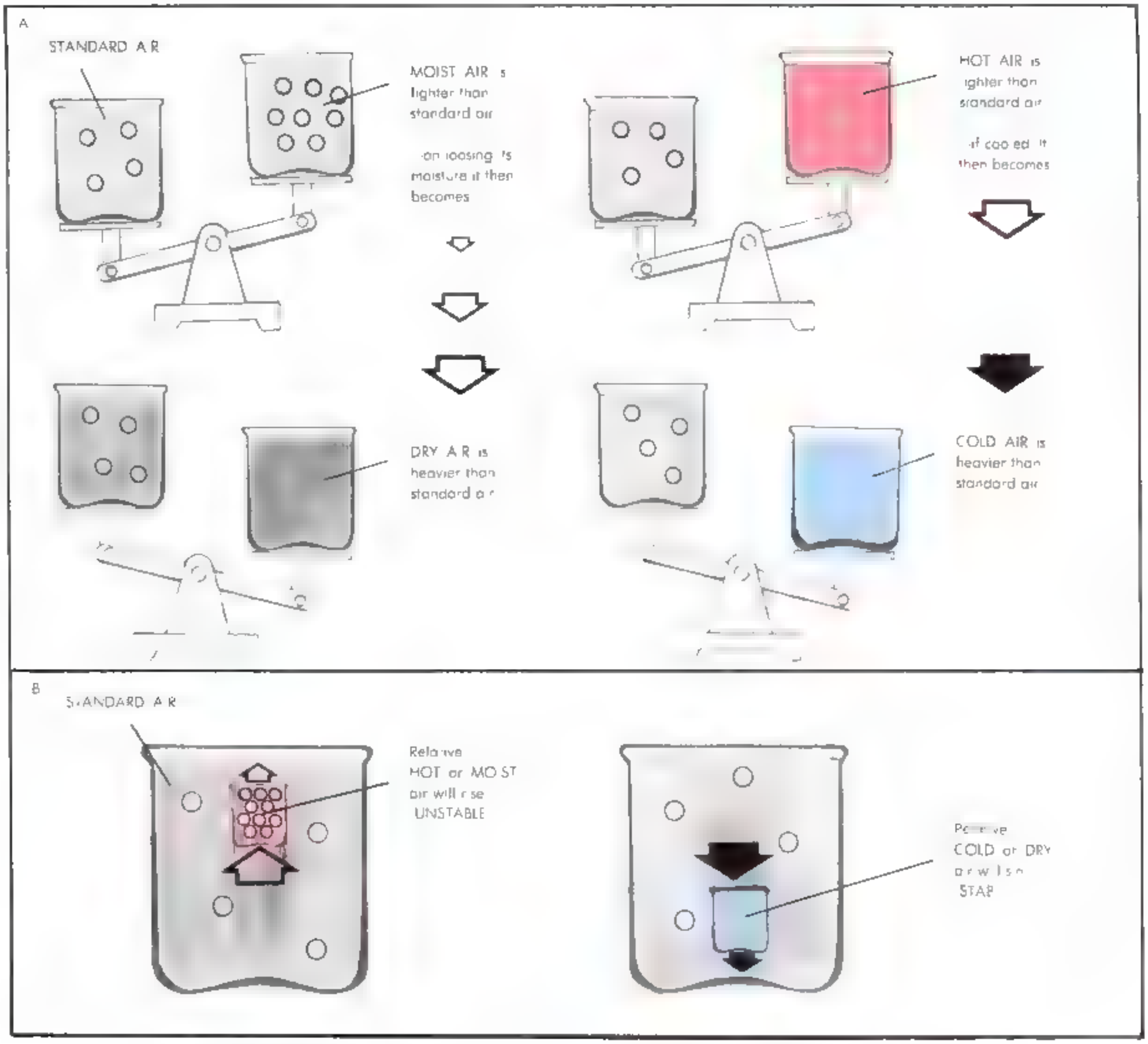

A
STANDARD AIR
MOIST AIR is lighter than standard air
on loosing its moisture it then becomes
DRY AIR is heavier than standard air
HOT AIR is lighter than standard air
if cooled it then becomes
COLD AIR is heavier than standard air
B
STANDARD AIR
Relative HOT or MOIST air will rise UNSTABLE
Relative COLD or DRY air will sink STABLE

Figure 6-1. Moisture Content and Temperature Determine Weight Of Air.

TEMPERATURE EFFECT

The air which is heated near the earth's surface on a hot summer day will rise. The speed and vertical extent of its travel depend on the temperature distribution of the atmosphere. Vertical air currents resulting from the rise of air can vary from the closely spaced upward and downward bumps felt on warm days when flying at low levels to the severe updrafts and downdrafts associated with thunderstorms

Since the temperature of air is an indication of its density, a comparison of temperatures from one level to another can approximate the degree of the atmosphere's stability; that is, how much it will tend to resist vertical motion.

LAPSE RATES

In Chapter 3 we saw that temperature usually decreases with altitude and that the rate at which it decreases is called the lapse rate. The lapse rate, commonly expressed in degrees per 1,000 feet, gives an estimate of the atmosphere's resistance to vertical motion. The degree of stability of the atmosphere may vary from layer to layer as indicated by changes of lapse rate with height.

When unsaturated air rises, its temperature decreases at the rate of 3°C (5½°F) per 1,000 feet. The air can be forced upward by being heated from below (figure 6-2A) or through forced ascension, such as up a mountain slope (figure 6-2B). Visualizing the rising air as a parcel which is separate from the surrounding atmosphere, the parcel in figure 6-2C gets larger with height This is because in its attempt to equalize pressure, the air expands, causing it to cool. Figure 6-2D shows the reverse process in which descending air is heated by compression.

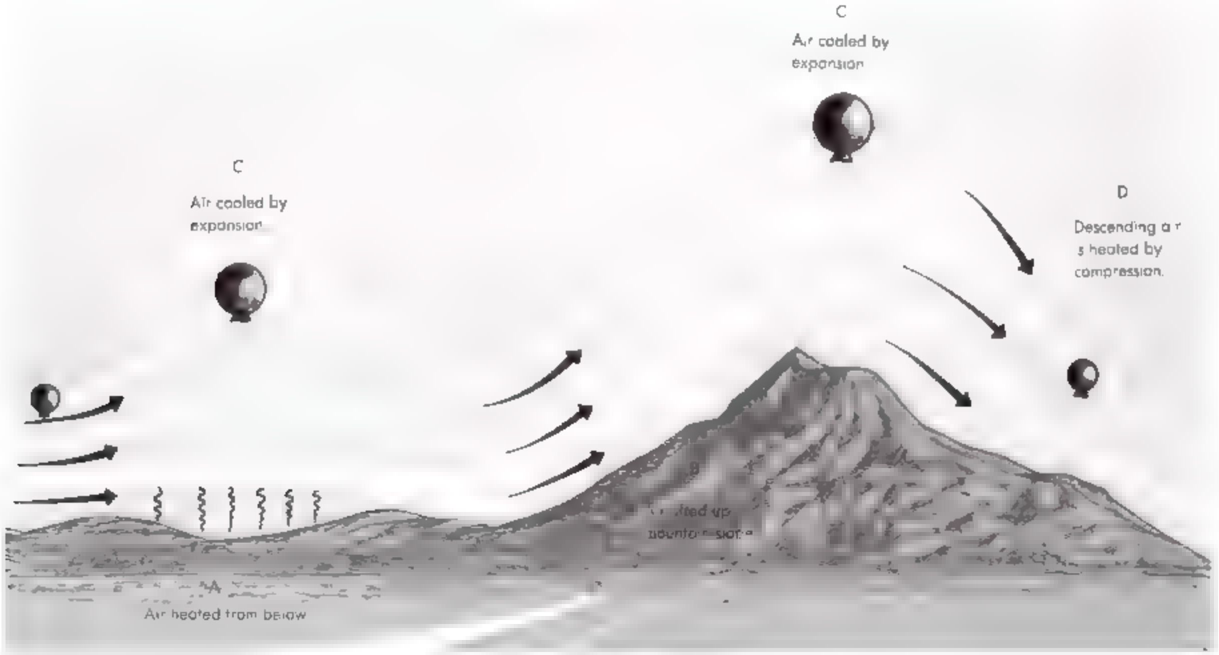


Figure 6-2. Effect Of Lifting Dry Air.

When saturated air rises, condensation occurs and the latent heat, used during the evaporation process, is released and absorbed by the air. This causes the air to cool at a slower rate (depending on the moisture content of that air) than that of unsaturated air.

The standard lapse rate of 2°C (3½°F) is used as a basis for calibrating aircraft altimeters and has no connection with determining the stability of the air However, the following may be concluded from the standard lapse rate:

- Unsaturated air, on the average, is stable
- Saturated air is normally unstable
- Saturated air at low temperatures, on the average, is stable.

The general conclusion is that air at moderate and high temperatures is normally either stable or unstable, depending upon the amount of moisture it contains.

CHANGES TO STABILITY

Stability runs the spectrum from absolutely stable to absolutely unstable, and the atmosphere usually is in a delicate balance somewhere in between. A change in the temperature lapse rate of an air mass can tip this balance. For example, surface heating or cooling aloft can make the air more unstable. On the other hand, surface cooling or warming aloft often tips the balance toward greater stability.

SOME EFFECTS OF STABILITY AND INSTABILITY

The degree of stability of the atmosphere helps to determine the type of clouds, if any, which form. For example, figure 6-3A shows that if very stable air is forced up a mountain slope, clouds will be layer-like with little vertical development and little or no turbulence. Unstable air, if forced up the slope, would cause considerable vertical development and turbulence in the clouds (figure 6-3B)

If air is subsiding (sinking), the heat of compression frequently causes an inversion of temperature, increasing the stability of the subsiding air (figure 6-4). Sometimes when this occurs, as in wintertime high pressure systems, a surface inversion formed by radiational cooling is already present. The subsidence-produced inversion, in this case, will intensify the surface inversion, placing a strong "lid" above smoke and haze. Poor visibility in the lower levels of the atmosphere results, especially near industrial areas. Such conditions frequently persist for days, notably in the Great Basin region of the western United States.

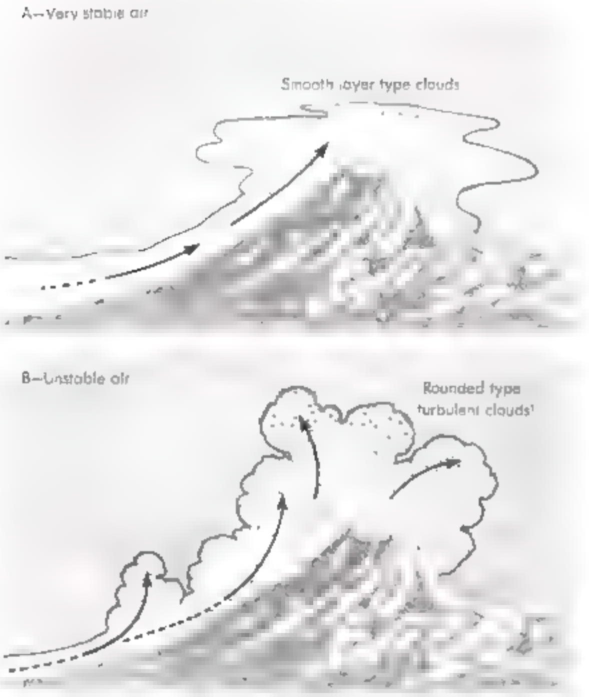


Figure 6-3. Stability Of Air Affects Type Of Cloud Formation.

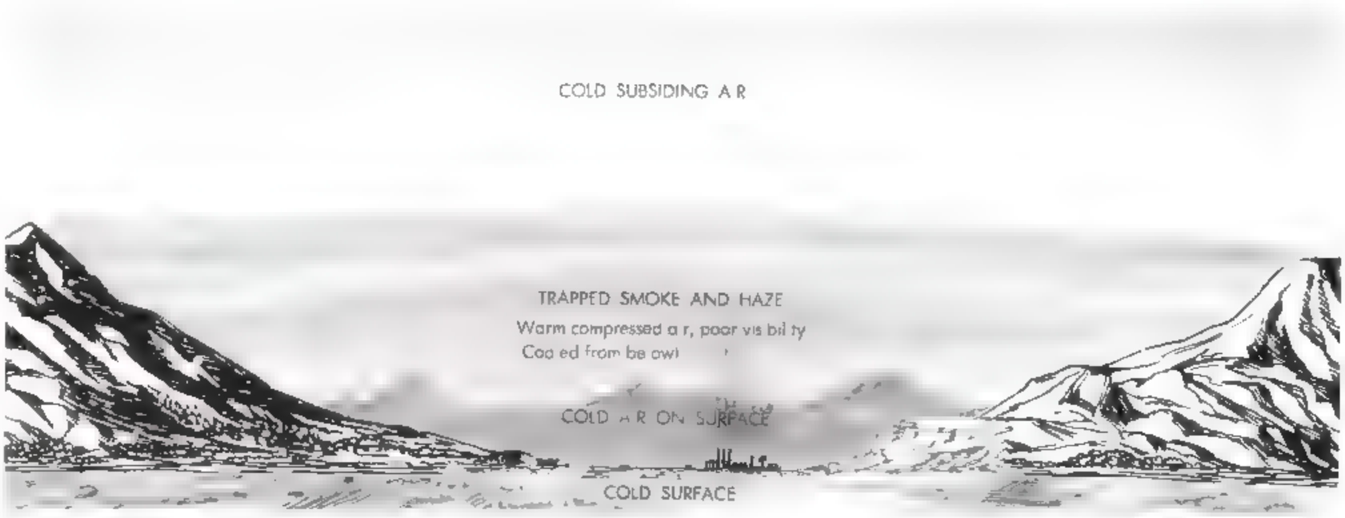


Figure 6-4. Surface Inversions (Temperature Increase With Altitude).

CHAPTER 7

CLOUDS

Clouds are weather signposts in the sky. They are visible evidence of the atmosphere's motions, water content, and degree of stability. In this sense, clouds are a friend to the flyer. They become an enemy, however, when they become too numerous or widespread, form at very low levels, or show extensive vertical development.

Knowledge of principal cloud types helps the aircrew member, when being briefed, to visualize expected weather conditions. Knowledge of cloud formation also helps the crew member recognize potential weather hazards inflight.

CLOUD COMPOSITION

Chapter 2 indicated that clouds are composed of minute liquid water droplets and/or ice crystals, depending on the temperatures within the clouds. When their temperature is between 0°C and -15°C, clouds are composed largely of supercooled water droplets, but usually contain some ice crystals. At temperatures below -15°C, clouds *usually* are composed entirely of ice crystals. However, supercooled droplets *sometimes* exist at temperatures as low as -60°C.

Cloud particles average about one-thousandth of an inch in diameter, but are clustered together closely enough to make them visible. They must grow enormously in order for precipitation to be produced, the average raindrop contains about one million times the water of that in a cloud droplet.

Condensation nuclei, such as dust, salt, and combustion by-products, compose the centers of cloud particles. Chapter 2 indicated that these water-absorbent impurities must be present for cloud droplets or ice crystals to form when the air becomes saturated

TYPES OF CLOUDS

The forms, species, and varieties of clouds are numerous enough to fill a book twice the size of this manual with illustrations and descriptions of each type. For the purpose of identification, aircrews need to be concerned only with the more basic cloud types, which may be divided into four "families." These families are: (1) low clouds, (2) middle clouds, (3) high clouds, and (4) clouds with extensive vertical development (figure 7-1). As discussed earlier, the altitude of the tropopause varies with latitude. The average heights of middle and high clouds within the troposphere vary with much the same proportionality. Low cloud levels vary little with latitude.

Low, middle, and high cloud families are further classified according to the way they are formed. Clouds formed by vertical currents of unstable air are called *cumulus*, meaning "accumulation" or "heap." They are characterized by their lumpy, billowy appearance. Turbulent flying conditions are usually found in and below cumuliform clouds. Clouds formed by the cooling of a stable layer are called *stratus*, meaning "spread out" or "layered." They are characterized by their uniform, sheetlike appearance. Flight within stratified clouds is relatively smooth

In addition to these subdivisions, the prefix *nimbo* or the suffix *nimbus*, which means raincloud, is added to the names of clouds which normally produce precipitation. Thus a horizontal cloud from which rain is falling is called *nimbostratus*, while a swelling cumulus that has grown into a thunderstorm is referred to as *cumulonimbus*.

Heights of the various cloud types are illustrated in figure 7-2

ALTITUDE OF BASE	CLOUD TYPE	ABBREVIATION
Bases of High Clouds Usually Above 6,000 Feet AGL	CIRRUS	CI
	CIRROCUMULUS	CC
	CIRROSTRATUS	CS
20,000 FEET		
Bases of Middle Cloud Range From 6,500 Feet AGL To 20,000 Feet AGL	ALTOCUMULUS	AC
	ALTOSTRATUS	AS
	NIMBOSTRATUS	NS
6,500 FEET		
Bases of Low Clouds Range From Surface To 6,500 Feet AGL	CUMULUS	CU
	CUMULONIMBUS	CB
	STRATOCUMULUS	SC
	STRATUS	ST
SURFACE		

*Cumulus and Cumulonimbus are clouds with vertical development. Their base is usually below 6,500 feet but may be slightly higher. The tops of the cumulonimbus sometimes exceed 60,000 feet.

NOTE Divisions between middle and high clouds can overlap and their limits may vary with latitude and season

Figure 7-1. Basic Cloud Types.

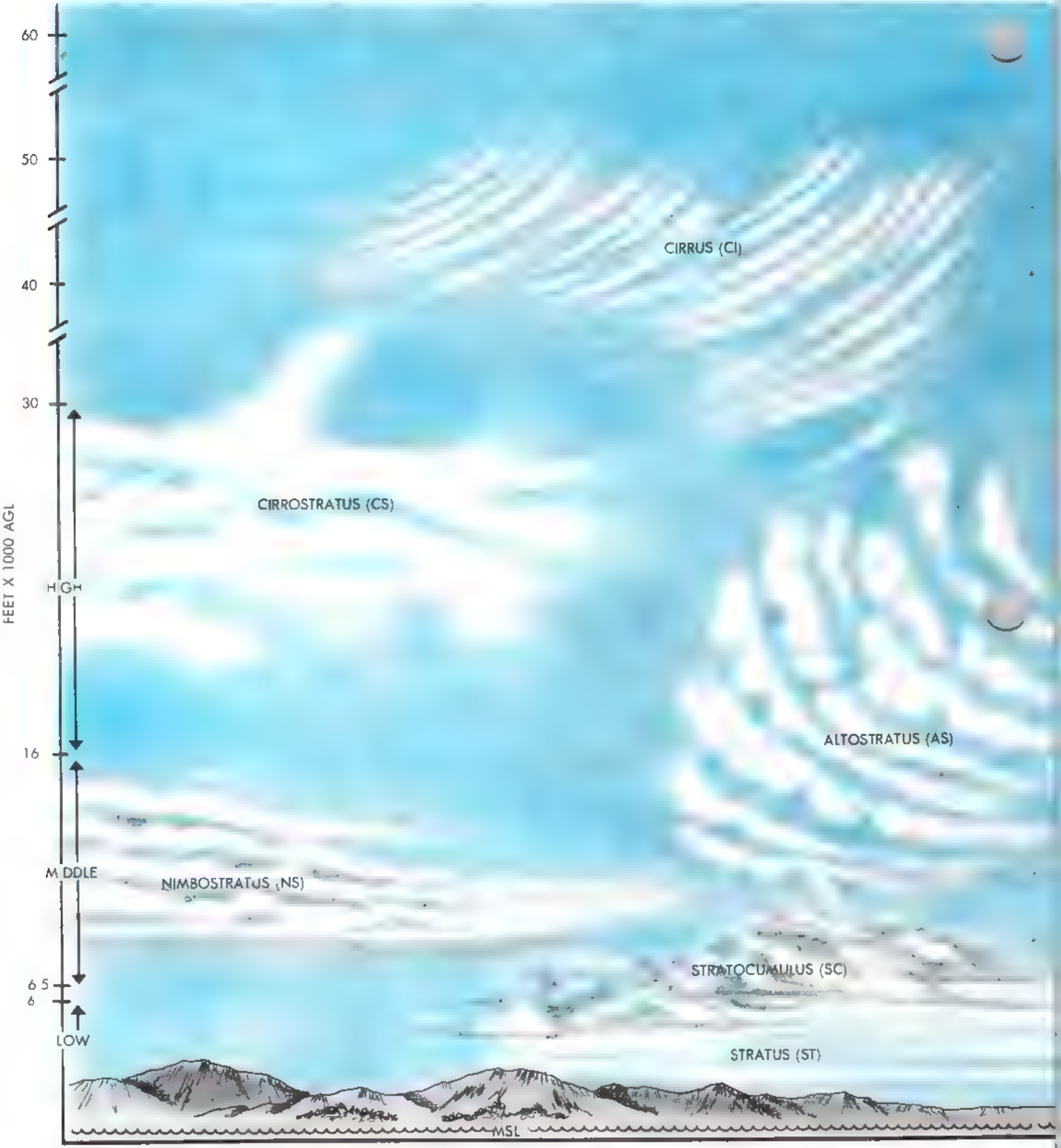
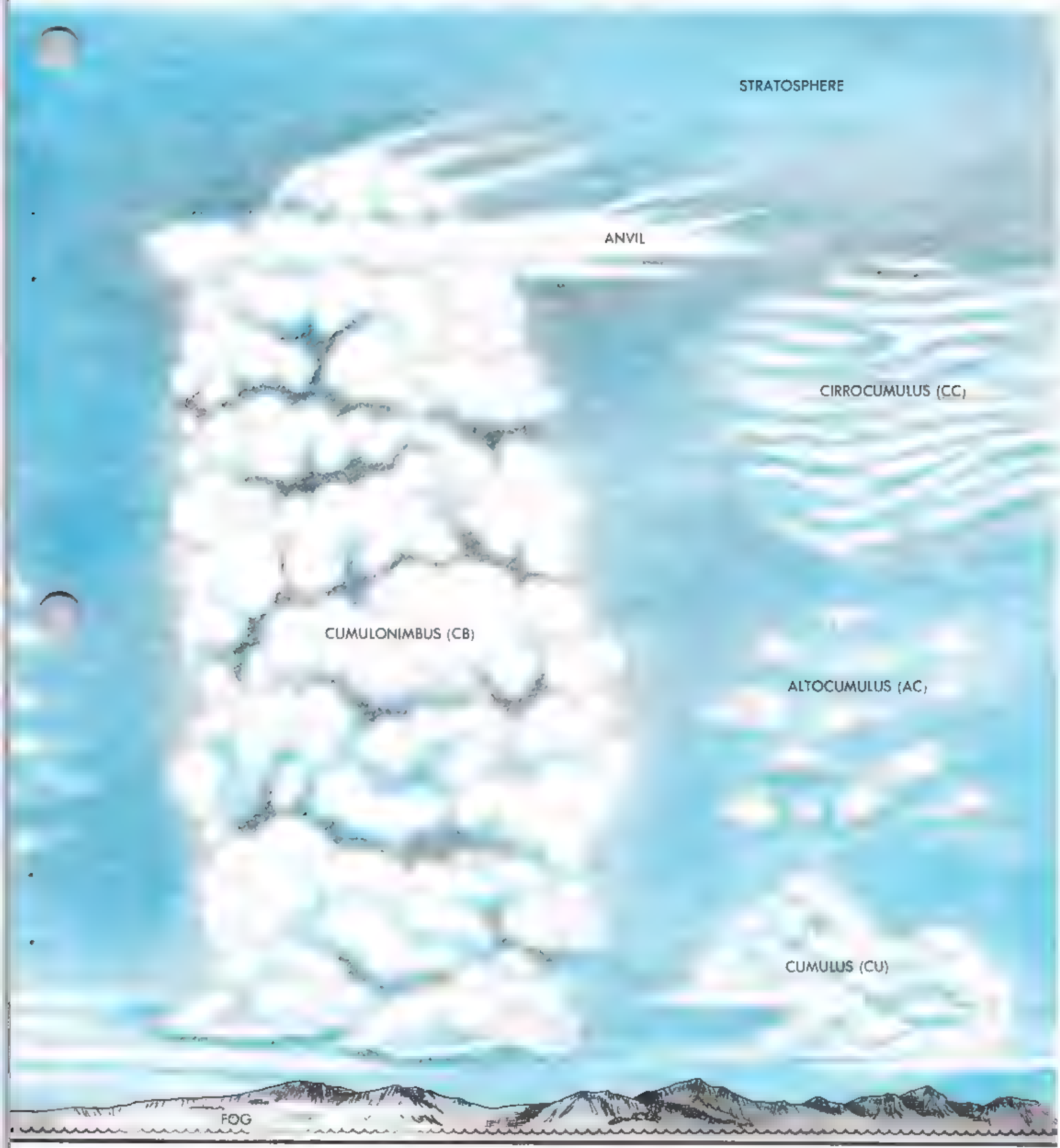


Figure 7-2. Cloud Heights.


STRATOSPHERE
ANVIL
CIRROCUMULUS (CC)
CUMULONIMBUS (CB)
ALTOCUMULUS (AC)
CUMULUS (CU)
FOG

CLOUD FORMATION AND STRUCTURE

When clouds form, the degree of stability of the air helps determine what type they will be. Cumuliform clouds, because of associated vertical air currents, always have some degree of turbulence within and beneath them. Since there is little or no vertical motion within stratiform clouds, little, if any, turbulence is experienced within them.

When air is forced to ascend, the structure of any clouds which form depends almost entirely on the air's stability prior to the lifting. For example, very stable air being forced up a mountain slope will remain sufficiently stable to prevent appreciable vertical development. Clouds will be layer-like with little or no turbulence. If the air which is forced upward is initially unstable, however, the mountain slope will itself increase the tendency for vertical development, and cumuliform clouds may grow considerably.

Sometimes stratified layers of clouds will change partly to cumuliform clouds as a result of heating from below (figure 7-3).

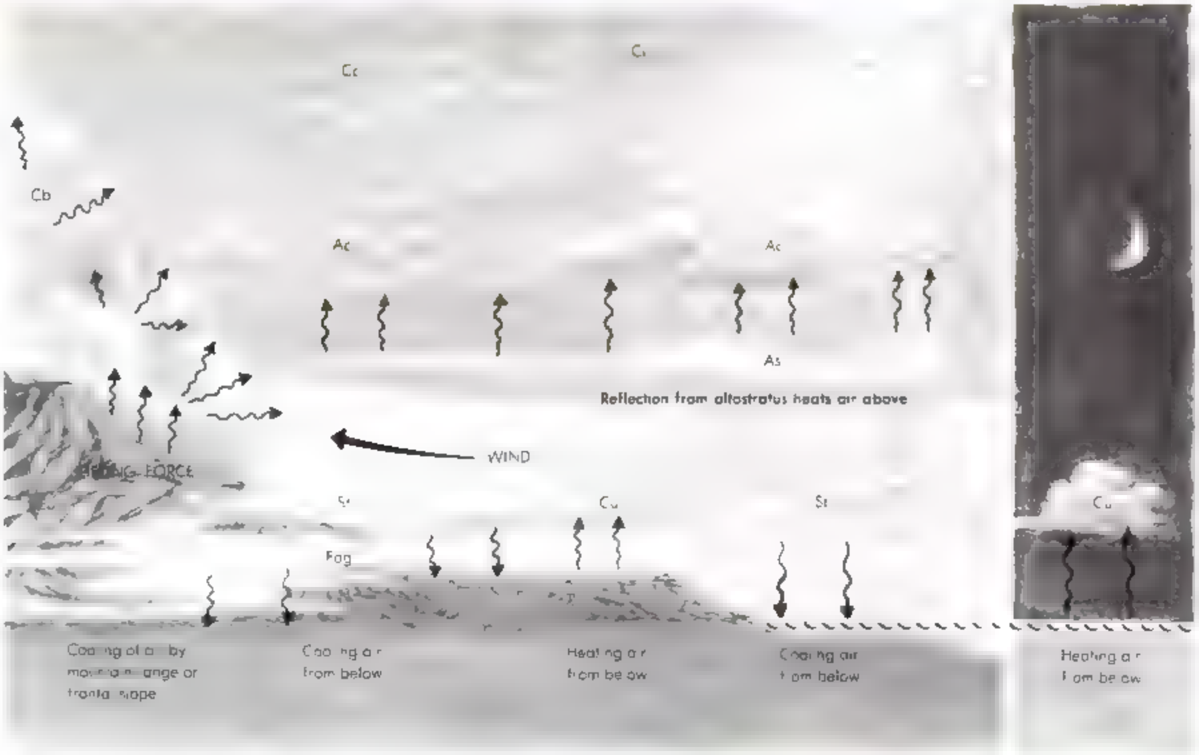


Figure 7-3. Various Factors Affecting Cloud Types.

Forced ascension of an entire layer produces similar conditions if the air is even slightly unstable. This transition in cloud formation can sometimes be noted when flying over a relatively smooth cloud deck with cumulus-like clouds beginning to project upward. Sometimes these projections appear as only random puffs and at other times in groups or in lines. Lines of cumuliform clouds projecting upward out of a horizontal cloud deck sometimes indicate a frontal zone (the boundary between different air masses). A similar cloud pattern often occurs at a coastline (figure 7-4) as a result of the temperature difference between the land and water. Mountain ranges, properly oriented relative to the flow of air, will produce lines of cumuliform clouds within what is otherwise a horizontal cloud layer.

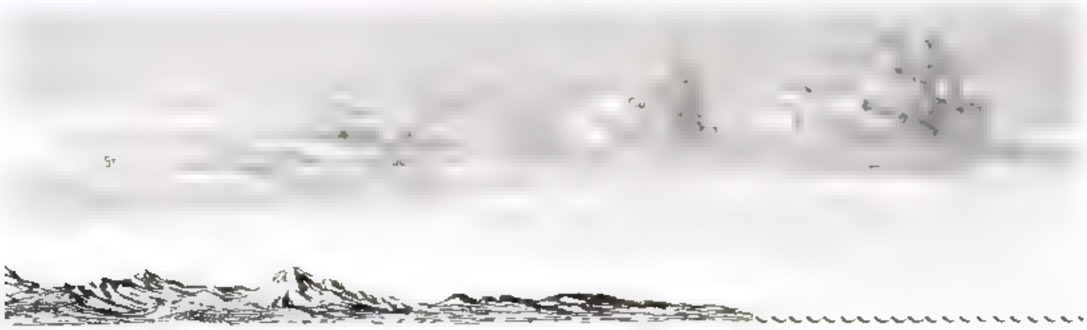


Figure 7-4. Stratus Becoming Stratocumulus and Cumulus At Coast Line.

CLOUD RECOGNITION

Low Clouds

This group of clouds consists of *stratus, stratocumulus, and cumulus.* The bases of these clouds range from near the surface to about 6,500 feet above the ground. If low clouds form below 50 feet, they are reclassified as fog. Low clouds are almost entirely water. However, these clouds may be composed of ice crystals or supercooled water droplets and may therefore contain icing conditions hazardous to aircraft. A brief description of each low cloud follows:

STRATUS (ST)

Stratus is a low, uniform, sheet-like cloud (figure 7-5). When associated with fog or precipitation, the combination can become a problem for VFR flying because of low ceilings and restricted visibility. The slow lifting of a fog layer often results in the formation of stratus. Lifting of stable air over sloping terrain also results in this type cloud. Finally, fog formed over the sea and driven across the coast by onshore winds may appear inland as stratus.

Although stratus contains little or no turbulence, temperatures near or below freezing can create hazardous icing conditions.

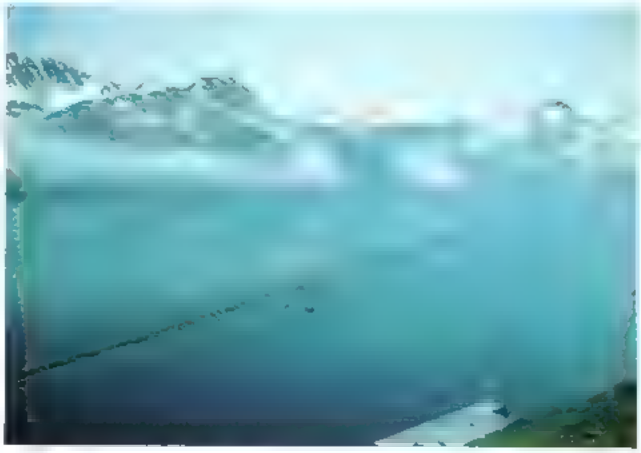


Figure 7-5. Stratus Clouds (ST).

STRATOCUMULUS (SC)

Stratocumulus are clouds having large, globular masses or rolls which look like balls of dirty cotton (figure 7-6). They often result from a layer of stable air being lifted and mixed by wind blowing over rough terrain. Stratocumulus also forms from the breaking up of a stratus layer or from the spreading out of cumulus clouds. Ceiling and visibility are usually better than with low stratus.

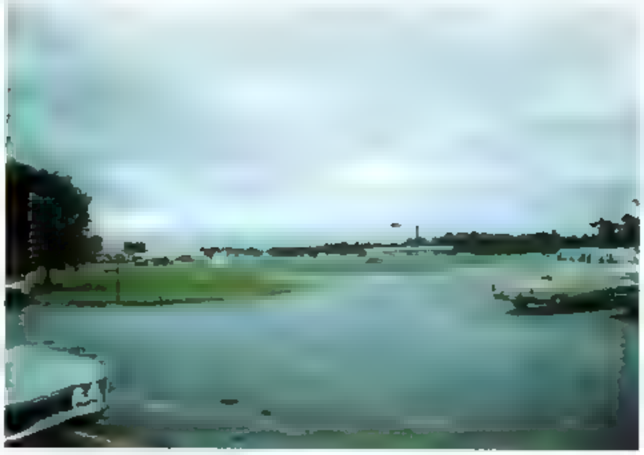


Figure 7-6. Stratocumulus Clouds (SC).

CUMULUS (CU)

Cumulus clouds form in convective currents caused by heating of the earth's surface. They can also form as the base of a cold air mass is warmed by passing over a relatively warm surface. Cumulus clouds are characterized by relatively flat bases and dome-shaped tops (figure 7-7). Fair weather cumulus indicates a shallow layer of instability. Some turbulence and no significant icing or precipitation can be expected. Although cumulus do not show extensive vertical development, continued growth may lead to towering cumulus and cumulonimbus clouds.

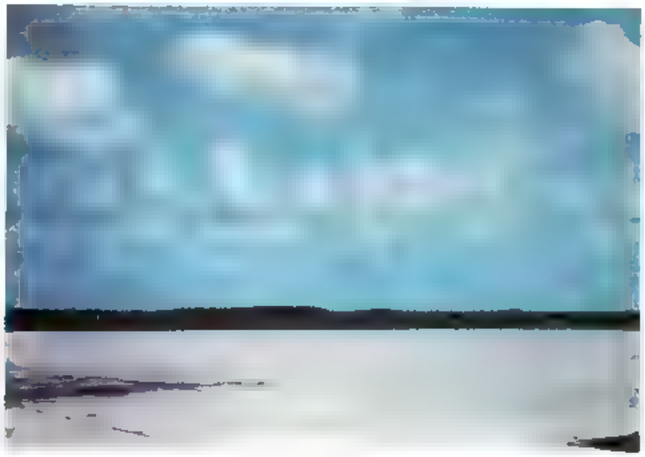


Figure 7-7. Cumulus Clouds (CU).

Middle Clouds

In the middle-cloud family are the *altostratus, altocumulus,* and *nimbostratus* clouds. The height of the bases of these clouds ranges from about 6,500 feet to about 20,000 feet above the terrain. These clouds may be composed of ice crystals or water droplets, much of which may be supercooled. Therefore, these clouds may contain significant icing conditions hazardous to aircraft.

Middle-cloud descriptions are:

ALTOSTRATUS (AS)

Altostratus are relatively uniform gray to blue sheets that cover the entire sky (figure 7-8). Altostratus is generally so dense that even through its thinner parts the sun shows dimly as through frosted glass. It often merges gradually into cirrostratus. Aircraft will experience little or no turbulence and may experience moderate icing in this type cloud.

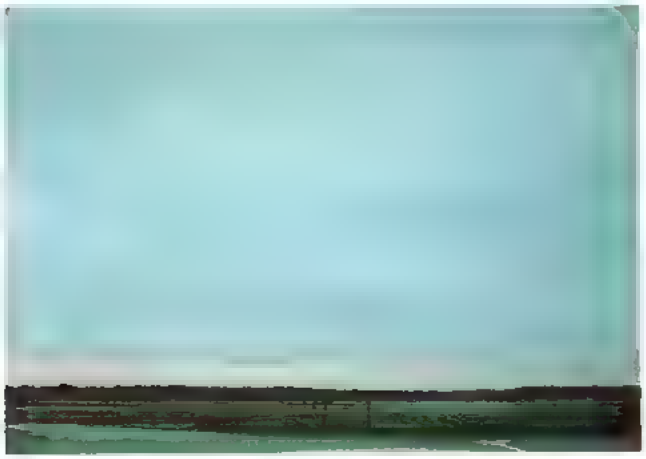


Figure 7-8. Altostratus Clouds (AS).

ALTOCUMULUS (AC)

Altocumulus are white or gray patches of solid cloud (figure 7-9). They are composed of water droplets, although at very low temperatures ice crystals may form. Altocumulus often develops from dissolving altostratus. Some turbulence and small amounts of icing will occur in altocumulus clouds.

A particularly dangerous variety of altocumulus is the *altocumulus standing lenticular (ACSL)*. It is discussed in the Special Cloud Types section of this chapter.

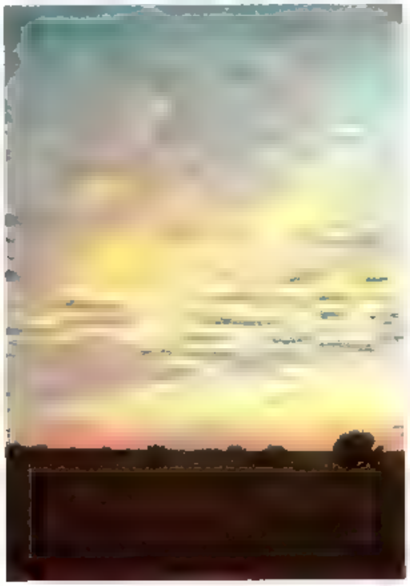


Figure 7-9. Altocumulus Clouds (AC).

NIMBOSTRATUS (NS)

Nimbostratus is a gray or dark massive cloud layer accompanied by continuous rain or snow or having a "wet" appearance (figure 7-10). This type cloud is classified as a middle-cloud although it may merge into very low stratus or stratocumulus. Nimbostratus clouds are really heavy, dense altostratus which can pose a serious icing problem if temperatures are near or below freezing.

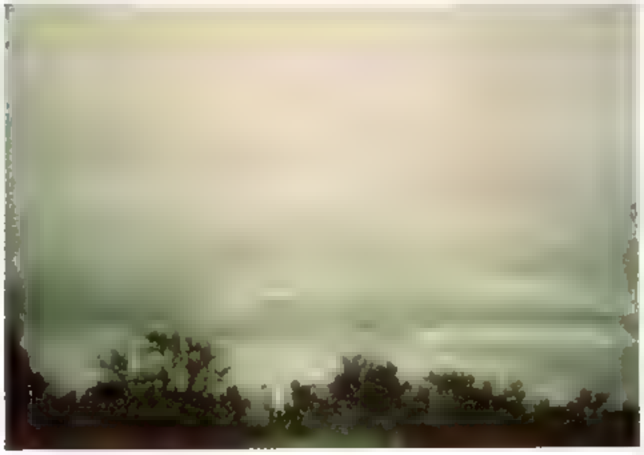


Figure 7-10. Nimbostratus Clouds (NS).

High Clouds

In this family are *cirrus, cirrostratus,* and *cirrocumulus* Each is referred to as *cirroform*. The height of the bases of these clouds ranges from about 16,000 to 45,000 feet in mid-latitudes The upper limit of these clouds may be as high as 60,000 feet in the tropics. Cirroform clouds are composed of ice crystals and, because of this, do not present a significant icing hazard.

High-cloud descriptions follow:

CIRRUS (CI)

Cirrus are thin, feather-like clouds in patches or narrow bands (figure 7-11). If these clouds are arranged in bands or connected with cirrostratus or altostratus, they may be a sign of approaching bad weather. Cirrus clouds often evolve from the upper part of thunderstorms or cumulonimbus clouds. They can blow away from the main cloud, or the main portion of the cloud may evaporate, leaving only the ice crystal top portion.

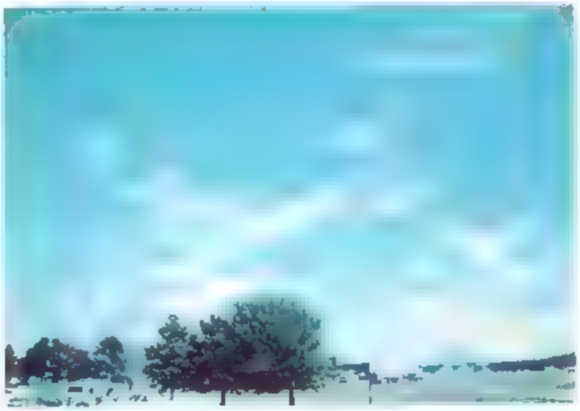


Figure 7-11. Cirrus Clouds (CI).

CIRROSTRATUS (CS)

Cirrostratus are thin, whitish cloud layers appearing like a sheet or veil (figure 7-12). The ice crystals composing cirrostratus may produce a halo effect. Cirrostratus occurs only in stable layers, therefore no turbulence and little icing can be expected. The greatest problem flying in cirriform clouds is restriction to visibility.

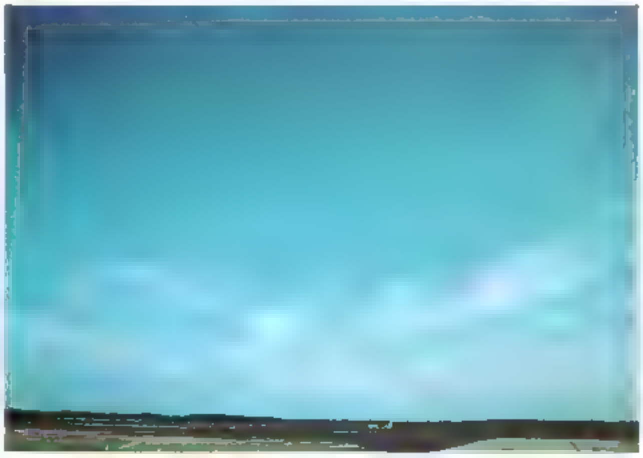


Figure 7-12. Cirrostratus Clouds (CS).

CIRROCUMULUS (CC)

Cirrocumulus are thin clouds which appear as small white flakes or patches of cotton (figure 7-13). This type cloud may result from the lifting of a shallow unstable layer, but more often it is developed from a layer of cirrostratus. Heat loss by radiation occurs from the top of the cirrus layer, and the cooler air on top sinks into the cloud, setting up shallow convective currents within the layer. Some turbulence may be experienced in cirrocumulus clouds

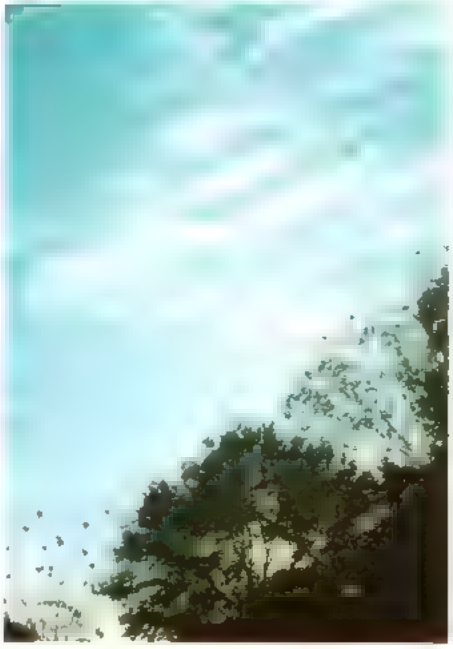


Figure 7-13. Cirrocumulus Clouds (CC).

Clouds With Extensive Vertical Development

Clouds in this family are *towering cumulus* and *cumulonimbus*. The height of their bases ranges from the low to the middle categories and their tops up through the high category. Their descriptions are.

TOWERING CUMULUS (TCU)

Towering cumulus is an important variety of the cumulus cloud, however it has greater vertical development than the cumulus (figure 7-14). It may be accompanied by turbulence and icing and is often present prior to thunderstorm formation.

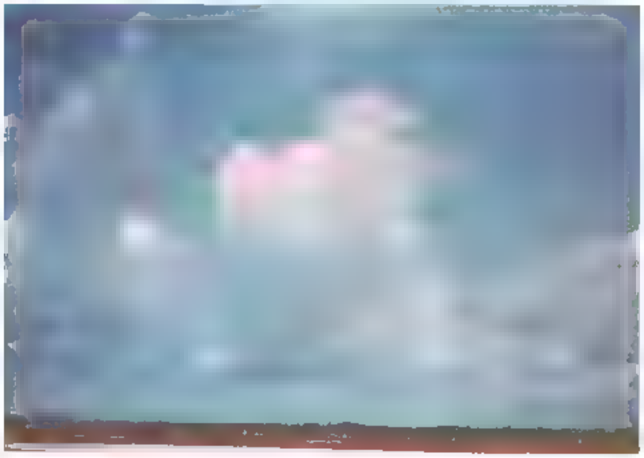


Figure 7-14. Towering Cumulus Clouds (TCU).

CUMULONIMBUS (CB)

Cumulonimbus are large, dense, towering clouds with cauliflower-like tops. The top portion of the cloud is often flattened into an anvil shape or consists of a cirrus formation resulting from ice crystals (figure 7-15).

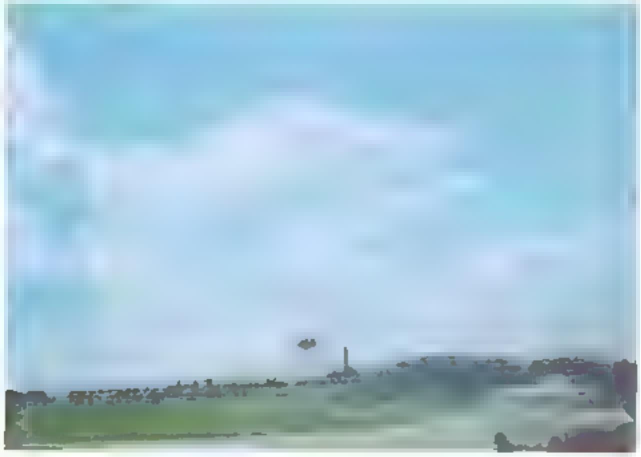


Figure 7-15. Cumulonimbus Clouds (CB).

Water droplets form the major portion of cumulonimbus clouds, but ice crystals appear in the upper portions. Cumulonimbus and thunderstorm are synonymous terms; they both result in strong winds, lightning, and intermittent showers. The well developed cumulonimbus may be the parent of the hailstorm and the tornado (figure 7-16).

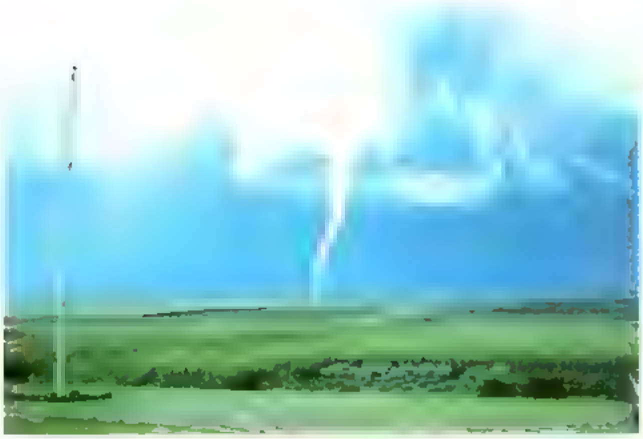


Figure 7-16. Tornado.

Flight Conditions Associated with Vertical Development Clouds

Isolated towering cumulus or cumulonimbus clouds seldom present a flight problem since these clouds normally can be circumnavigated. However, these clouds may rapidly develop in groups or lines of cumulonimbus. They may also become embedded and hidden in stratiform clouds, resulting in hazardous instrument flight conditions. Turbulence and icing may be severe enough to cause structural failure to the aircraft. Avoid flying near or directly under cumulonimbus clouds. (See Chapter 13, Thunderstorms, Lightning, and Electrostatic Discharge, and Attachment 1, Ground-Based and Airborne Radar.)

Special Cloud Types

ALTOCUMULUS STANDING LENTICULAR (ACSL)

ACSL clouds are formed on the crests of waves created by barriers in the wind flow (figure 7-17). Condensation in the ascending portion of the wave forms the cloud. In the descending portion of the wave, the cloud evaporates. Thus, the cloud appears not to move although the wind can be quite strong blowing through it. These clouds must be avoided since their presence is a good indication of strong turbulence. (See Chapter 10, Mountain Wave Turbulence.)

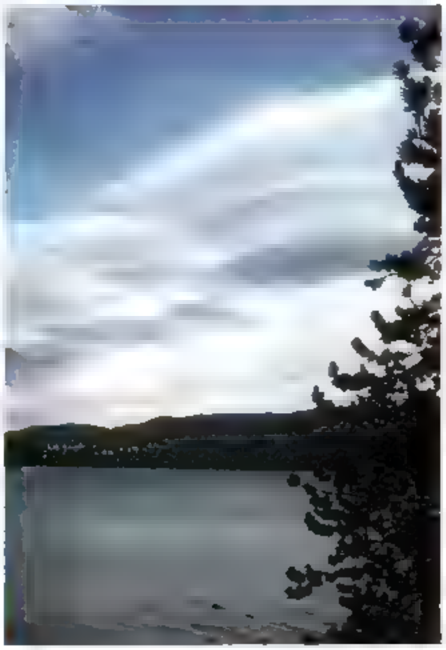


Figure 7-17. Altocumulus Standing Lenticular Clouds (ACSL).

ROTOR CLOUDS

Rotor clouds form on the lee side of mountains. The rotor cloud looks like a line of small cumulus clouds parallel to the mountain (figure 7-18). The rotor cloud gives a visible appearance of turbulence associated with the mountain wave. Aircrews may encounter severe turbulence in the vicinity of the rotor cloud. Further description is contained in Chapter 10, Mountain Wave Turbulence.

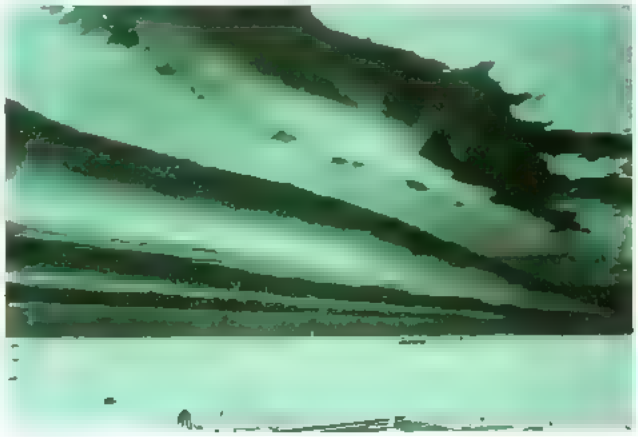


Figure 7-18. Rotor Clouds.

VIRGA

Virga appears as wisps or streaks of water or ice particles attached to the under-surface of a cloud but not reaching the earth's surface (figure 7-19). Virga usually trails from altocumulus and altostratus clouds, but occasionally can be seen trailing from high level cumuliform clouds. Precipitation falling from these high-based clouds evaporates, cooling the air and creating a downdraft.

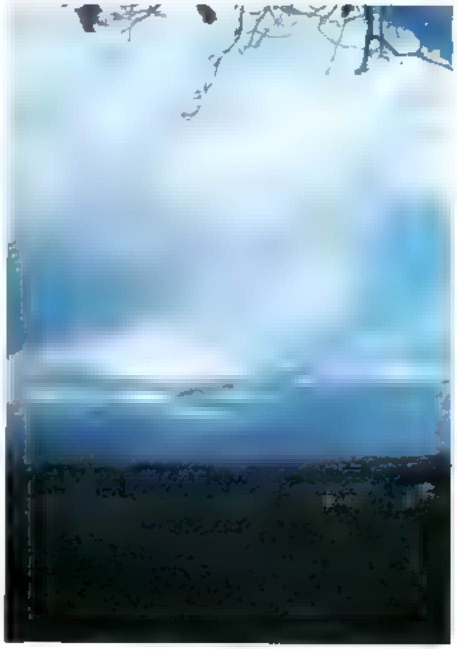


Figure 7-19. Virga.

CONDENSATION TRAILS (CONTRAILS)

Contrails are clouds which form in the wake of an aircraft when the atmosphere at flight level is sufficiently cold and humid (figure 7-20). In a tactical environment, contrails can highlight aircraft position. Aircrews should be aware of the forecast contrail level during mission planning. The two types of contrails are *aerodynamic* and *engine exhaust*.

Aerodynamic contrails are caused by the reduction of air pressure when air flows at high speed past an airfoil. These trails are of short duration. A small change in altitude or reduction in speed may stop their formation.

Engine exhaust contrails form when water vapor in the exhaust gas mixes with and saturates the air through which the aircraft is flying The maximum period of exhaust contrail formation is in the winter season. In very cold arctic air, these contrails may even form at the surface. A change in altitude or power setting may eliminate exhaust contrails.

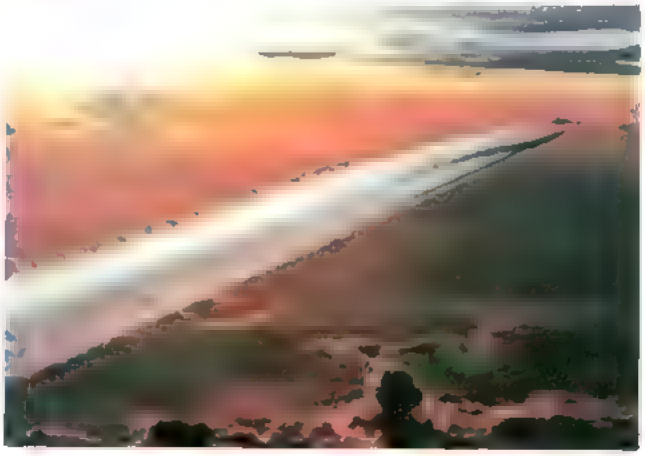


Figure 7-20. Contrails.

CHAPTER 8

AIR MASSES

An *air mass* is a body of air extending over a large area (usually 1,000 miles or more across). Properties of temperature and moisture are fairly constant throughout the air mass. Horizontal changes of these properties are usually very gradual. The terrain surface beneath the air mass is the primary factor in determining air mass characteristics.

SOURCE REGIONS

The region where an air mass acquires its identifying properties of temperature and moisture is called its source region. The ideal source region has a uniform surface (all land or all water), a uniform temperature, and is an area in which air stagnates to form high pressure systems. In general, the best source regions for air masses are large snow or ice-covered polar regions, tropical oceans, and large desert areas. Mid-latitudes are poor source regions. Air has little opportunity to stagnate in the mid-latitudes since weather and pressure patterns are on the move.

Source regions for air masses affecting North America are shown in figure 8-1. These regions include the plains of northern Canada, the polar ice cap, the broad ocean areas of the North Atlantic and North Pacific, the Atlantic and Pacific near 30°N latitude, the Gulf of Mexico, and the arid regions of the southwestern United States and northern Mexico.

AIR MASS CLASSIFICATION

A detailed world-wide air mass analysis is beyond the scope and space of this manual. This section presents a more general description of the air masses affecting the weather of the continental United States.

- Air stagnating over northern continental regions forms continental polar (cP) or continental arctic air masses They are cold and dry, and their source region is very stable.
- Maritime polar (mP) air masses form over northern oceanic areas. They are generally not as cold as continental polar air masses (especially in winter), have a higher moisture content, and can be either stable or unstable.
- Maritime tropical (mT) air masses form over warm oceanic areas nearer the equator. They are very humid and generally are the most unstable of all.
- Arid continental regions give rise to continental tropical (cT) air masses, which are hot, dry, and unstable. But due to the absence of water vapor, they produce few showers and the showers that do develop have comparatively high bases and yield small rainfall amounts

AIR MASS MODIFICATION

Just as an air mass tends to take on the temperature and moisture properties of its source region, it also tends to

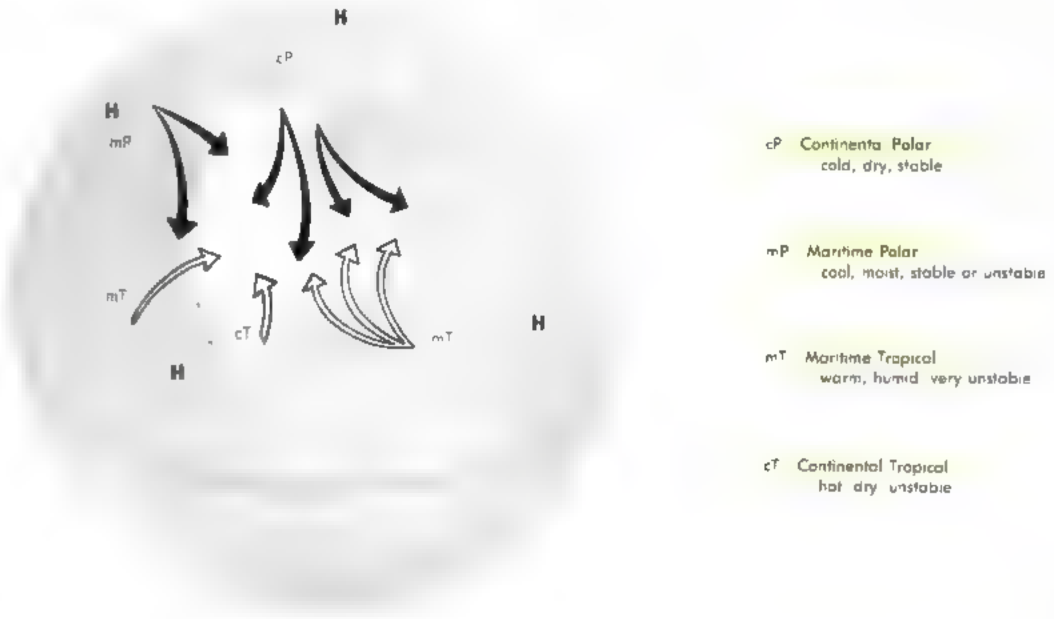


Figure 8-1. Typical Air Mass Source Regions.

have these same properties changed when it moves out of its source region. The degree of modification of an air mass is dependent on:

- The speed with which it travels.
- The nature of the region it moves over
- The temperature difference between the new surface and the air mass
- The depth of the air mass.

The ways in which various atmospheric processes modify an air mass should be considered Keep in mind that more than one of the processes is usually in progress at the same time.

Warming from Below

If an air mass flows over a surface warmer than itself, heat energy will flow from the ground to the air Convective currents carry the heat to higher and higher levels. The end result is that the air mass will become gradually more unstable or less resistant to vertical currents

The results can be presented pictorially by thinking of the condition as water boiling on a stove (figure 8-2). If it is heated from below, the liquid becomes unstable and begins to boil. Flying in a situation of this type would be bumpy due to the *thermals* or convective currents rising from the ground. Fortunately, most aircraft can be flown high enough so that they are above the tops of the thermals rising from the ground. Aircrews flying in the same area over a period of time will notice a gradual buildup in the heights of thermals from day to day Over desert areas the instability created during daylight hours is not completely nullified by night cooling and permits instability to gradually reach higher and higher levels (figure 8-3). These thermal or convective currents can be thought of as a mechanism used by nature for conversion of heat energy into energy of movement. The turbulence felt in thermals is proportional to the amount of heat energy being absorbed by the earth's surface below

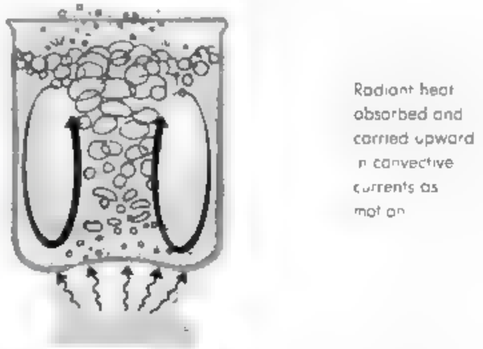
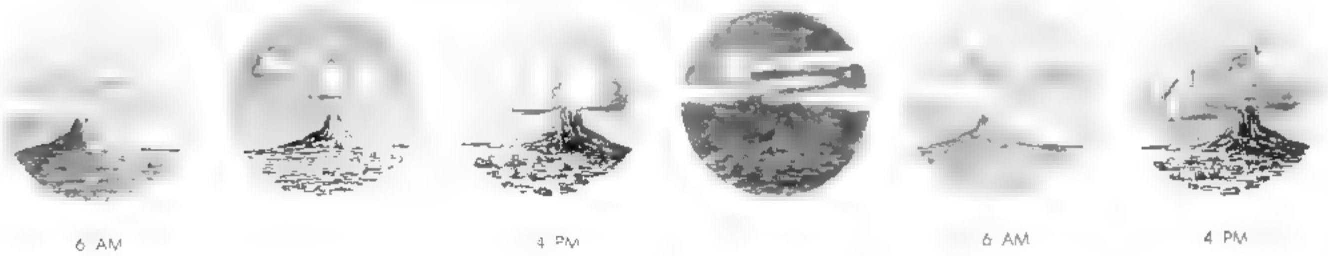

Radiant heat absorbed and carried upward in convective currents as motion

Figure 8-2. Heating From Below Causes Instability.



Instability builds when night cooling does not nullify day heating

Figure 8-3. Diurnal Variation and Instability Buildup.

The important thing to remember is that whenever heating is accomplished from below, the tendency is for the air to become more unstable. This sometimes serves to condition an air mass for hazardous weather later on. This situation normally occurs during the hours when the surface is absorbing the greatest amount of heat from the sun (figure 8-4)

For example, during the summer months the waters of the Great Lakes store a large amount of heat energy. Water temperatures change much slower than land surface temperatures. Therefore, in the fall months the temperature-drop of the lakes lags far behind that of the neighboring land surfaces, making the water warmer than the land

Figure 8-5 shows an outbreak of cold air from the north flowing over the lakes creating a tremendous temperature differential between the air and the surface of the lakes and resulting in considerable warming of the lower levels of the air In addition to the heating, the lakes have added some moisture to the air. The result is instability with snow showers forming over the lakes and spreading downwind over the areas to the south of the lakes.

Aircrews flying between New England and Bermuda nearly always report cumulus clouds beginning about 60-80 miles southeast of New York and continuing to within 40-50 miles of Bermuda. This is another example of heating from below. The cumulus activity is the result of warm ocean temperatures of the Gulf Stream.

Cooling from Below

If an air mass flows over a surface colder than itself, heat energy will flow from the air to the ground. This cooling from below tends to increase the stability of the air mass. If the air is cooled to its dew point, stratus and/or fog forms.

This can also be presented pictorially (figure 8-6) if we think of the condition as placing a pan of boiling water

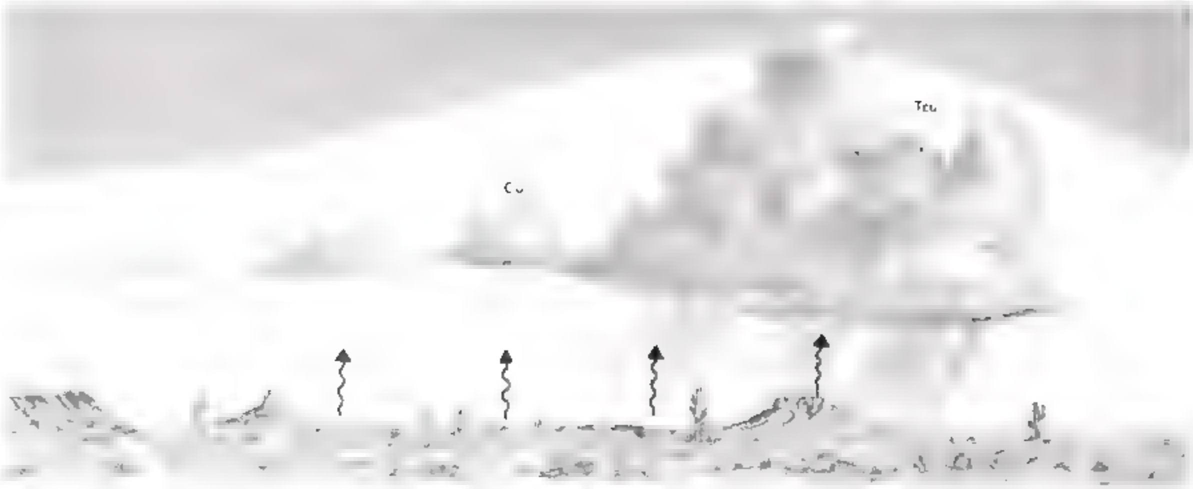


Figure 8-4. Heating Moist Air From Below.

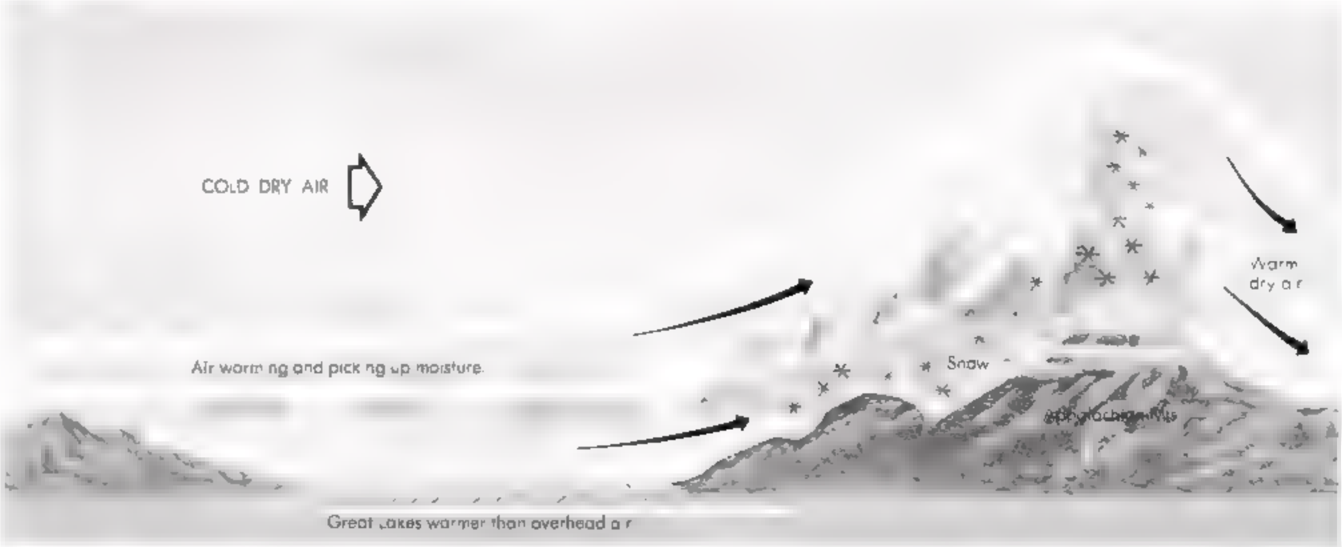
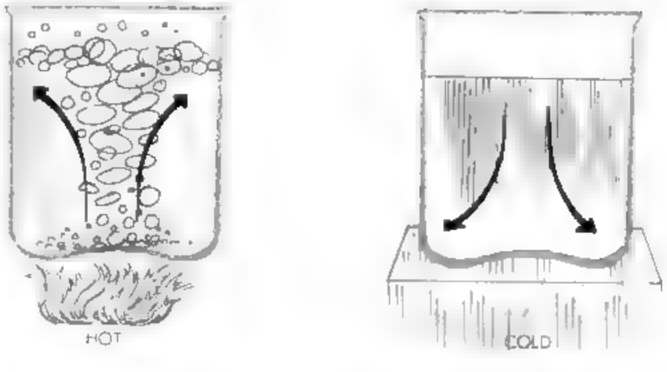

COLD DRY AIR
Warm dry air
Air warming and picking up moisture
Snow
Appalachian Mts
Great Lakes warmer than overhead air

Figure 8-5. Heating Cold, Dry Air From Below And Adding Moisture.



Heat flows downward
to colder surface,
mixture stabilizes

Figure 8-6. Cooling From Below Improves Stability.

on a cake of ice. As the liquid is cooled from below, it stops boiling and becomes stable.

One important thing to remember in this situation is that there is no limit to how stable an air mass can become. Prolonged cooling in the lower layers sometimes sets up conditions so stable that daytime heating cannot overcome the extreme stability.

There are many examples of this in the United States, especially in areas where topography helps to maintain stability by trapping stable air and not allowing circulation or drainage. Two of the most interesting of these are the Sacramento Valley of California and the Medford Valley of Oregon. Both have occasion to become filled with very stable and moist air which leads to low stratus formations and fog that can last for weeks (figure 8-7).

In the southeastern United States a high pressure area is normally centered off the coast of Florida. The resulting circulation makes a wide sweep over the Atlantic to pick up moisture, enters the Gulf Coast, and moves slowly northward, When this happens over the colder land in the early spring or fall months as shown in figure 8-8, it is not uncommon to see most of the eastern United States covered with low stratus. The balance between sufficient heating to keep the air clear and cooling to allow condensation within a stable air mass is sometimes so small that a minor change of temperature one way or the other may change the complexion of the weather over a large area in a relatively short time.

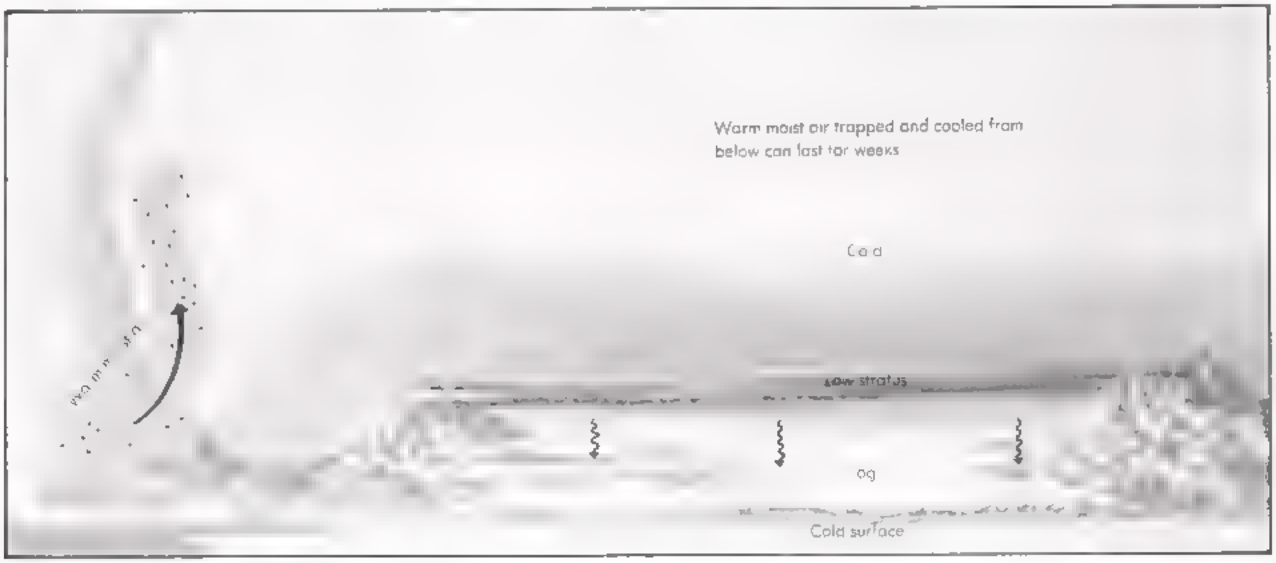

Warm moist air trapped and cooled from below can last for weeks
Cold
Low stratus
Fog
Cold surface

Figure 8-7. Warm, Moist Air Trapped And Cooled From Below.

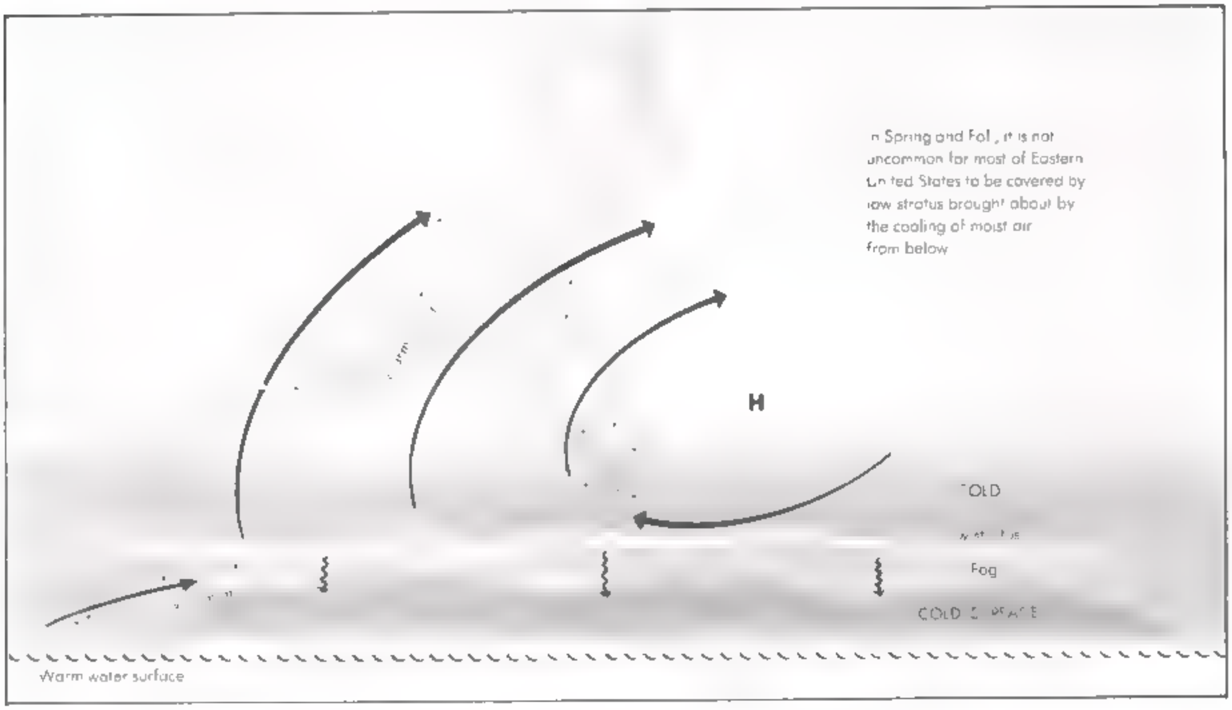

In Spring and Fall, it is not uncommon for most of Eastern United States to be covered by low stratus brought about by the cooling of moist air from below
H
COLD
Fog
COLD SURFACE
Warm water surface

Figure 8-8. Warm, Moist Air Cooled From Below.

The long arctic nights are responsible for the formation of very pronounced low-level stability in interior Alaska. Inversions of temperature up to 50°F are not uncommon (figure 8-9).

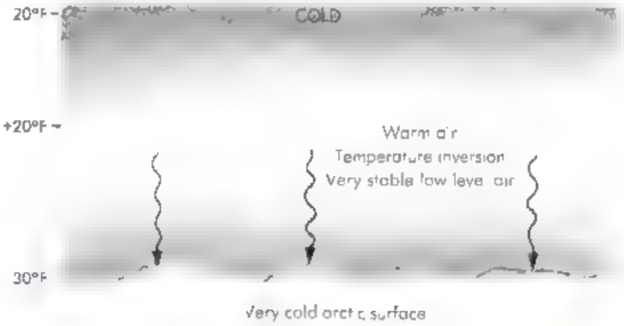


Figure 8-9. Inversion-Produced Stable Layer.

Other Modifying Causes

Addition of water vapor to the lower layers of an air mass *decreases* its stability. Moisture is added by evaporation from water surfaces, moist ground, liquid precipitation, or sublimation from ice or snow surfaces and solid precipitation.

Removal of water vapor from lower layers of an air mass *increases* its stability. Moisture is removed by condensation, sublimation, or precipitation.

Lifting of the air mass decreases its stability. Lifting may be produced by the air being warmed from below. By air being forced up the slopes of mountains (orographic lifting), or in the warm air mass when it is forced up by having colder air move under it.

Ascending currents result in expansion and cooling of the air mass. Cooling increases the relative humidity, and if the amount of cooling is sufficient, the air becomes saturated. Clouds then form and precipitation may or may not result, depending on other factors.

Sinking of the air mass increases its stability. Descending currents are present if air is forced down from a colder air mass or if air moves from mountains to lowlands. Air may also sink and spread out as a result of its own weight (subsidence). The relative humidity of descending air decreases due to warming of the air as it is compressed. For this reason, clouds usually dissipate in descending air currents (figure 8-10).

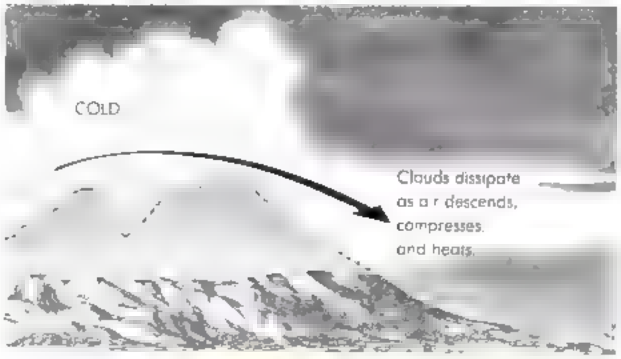


Figure 8-10. Sinking Air (Subsidence) Increases Stability.

Stability

Stability of an air mass determines its typical weather characteristics. Assuming moisture is available, characteristics typical of an unstable and a stable air mass are as follows.

Stable Air Mass	Unstable Air Mass
Stratiform clouds and fog	Cumuliform clouds
Continuous precipitation	Showery precipitation
Smooth air	Rough air (turbulence)
Fair to poor visibility	Good visibility (except in precipitation, blowing sand or snow)

CHAPTER 9

FRONTS

Fronts are transition *zones* between air masses that have different densities (figure 9-1). The density of air is primarily controlled by the temperature and humidity of the air. Therefore, fronts in the mid latitudes usually form between tropical and polar air masses

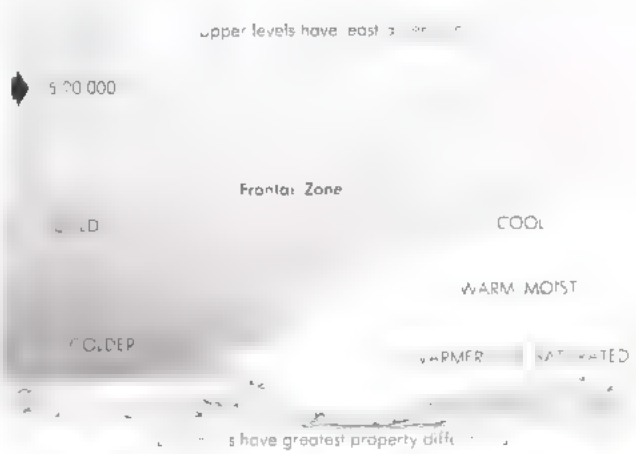


Figure 9-1. Frontal Zone.

Frontal zones, normally many miles in width, are most easily detected when the air masses have vastly different properties. Frontal zones are more difficult to locate over the ocean or other data sparse areas. Many times, fronts can be located only on the basis of cloud pictures from weather satellites (figure 9-2)

The frontal zone is indicated on a surface weather chart by a line. Designs on the line indicate the type of front and the direction of movement. In local weather stations, fronts may also be indicated by colored lines (figure 9-3).

Fronts are especially important to the aircrew. Specific weather conditions precede and follow a front as it moves through an area. In addition, weather associated with one section of a front is frequently different from the weather in other sections of the same front. Frontal weather varies according to the type of front formed. But most important, many weather hazards to aviation may accompany a frontal system.

DISCONTINUITIES ACROSS FRONTS

Differences in the properties of adjacent air masses, such as temperature, moisture, and wind, are used to locate fronts both aloft and at the surface.

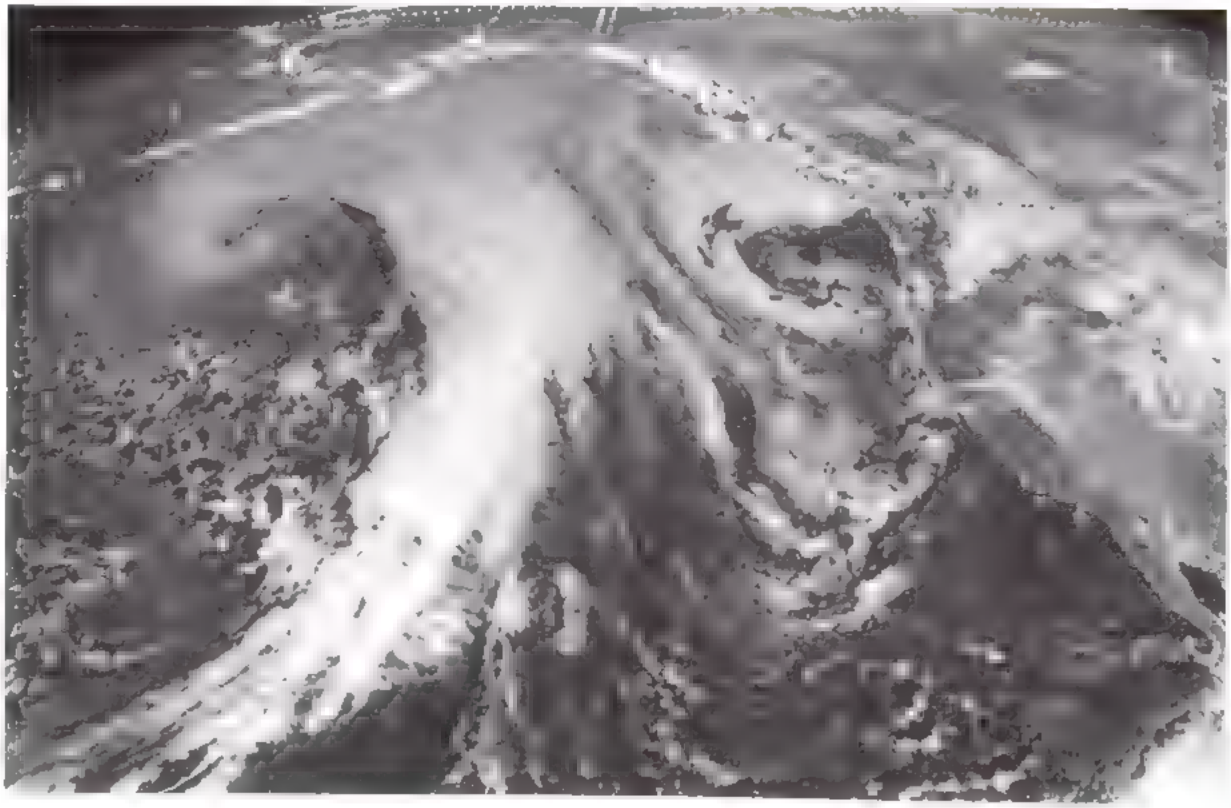
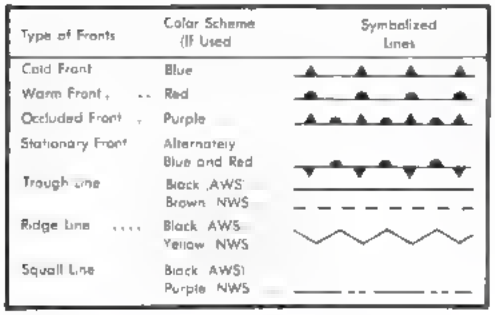


Figure 9-2. Satellite Picture Of A Front in the Gulf of Alaska.



Type of Fronts	Color Scheme (If Used)	Symbolized Lines
Cold Front	Blue	▲ ▲ ▲ ▲
Warm Front	Red	● ● ● ●
Occluded Front	Purple	▲ ● ▲ ● ▲ ● ▲
Stationary Front	Alternately Blue and Red	▼ ● ▼ ● ▼ ● ▼
Trough Line	Black (AWS) Brown (NWS)	——————— – – – – – – –
Ridge Line	Black (AWS) Yellow (NWS)	/\/\/\/\/\/\
Squall Line	Black (AWS) Purple (NWS)	—— – · – —— – · –

Figure 9-3. Symbols for Various Types of Fronts.

Temperature

Temperature is one of the most easily recognized discontinuities across a front. At the surface the passage of a front usually causes a noticeable temperature change. When flying through a front, the aircrew will note a significant change in temperature, especially at low altitudes.

The amount and rate of change are a partial indication of the front's intensity. Strong (narrow) fronts are accompanied by abrupt and sizeable temperature changes. Weak or diffused fronts are characterized by gradual and minor changes in temperature.

The point to remember when flying through a front is that the temperature change, even when gradual, is faster and more pronounced than a change during a flight entirely within one air mass. Thus, for safety, obtain a new altimeter setting after flying through a front. Chapter 4 discussed the effect of a temperature change on the aircraft altimeter.

Dew Point

The dew-point temperature, together with the air temperature, gives a rough indication of the relative humidity of the air. Dew point and temperature-dewpoint-spread usually differ across a front. The difference helps identify the front and may give a clue to differences of cloudiness and fog.

Wind

Near the earth's surface the discontinuity of wind across a front is primarily a matter of change in direction. Wind speed often is very much the same on both sides of a front. In many cases, however, when flying from warm to cold air, the wind speed increases abrupty since, in general, wind speeds are greater in the cold air mass.

Be alert for a sudden change in wind when flying in the vicinity of a front. The rapid change in wind creates wind shear which can be extremely hazardous, particularly during the approach or departure phases of flight.

Pressure

Since a front lies in a pressure trough, the pressure is higher on both sides of the front (figure 9-4). Thus, when a front is approaching a station, the pressure is usually decreasing. Pressure normally arises abruptly or becomes steady after frontal passage. The important thing to remember is that when crossing a front, a difference in pressure will be encountered. Be especially alert to keep the aircraft altimeter setting current.

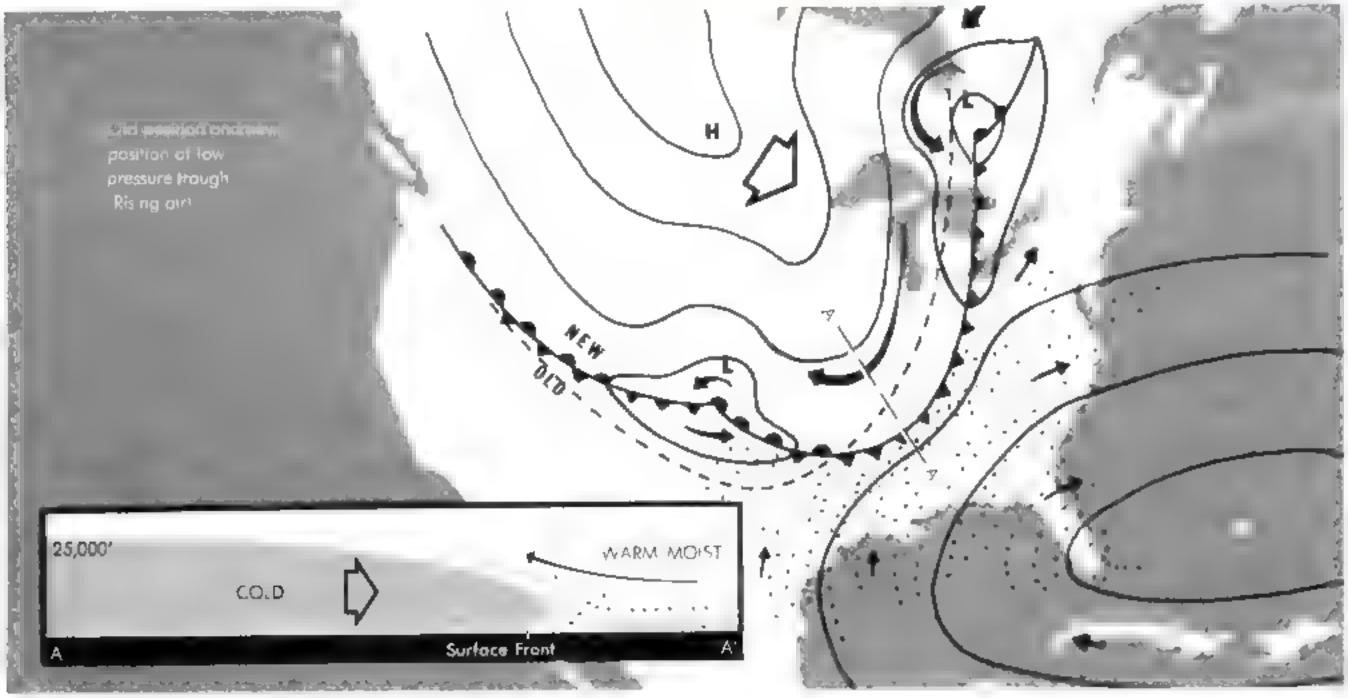


Figure 9-4. Polar Front Follows Low Pressure Trough.

COLD FRONTS

The leading edge of an advancing cold air mass is called a *cold front.* That is, the cold air is overtaking and replacing warmer air. Surface friction holds back the air in contact with the earth's surface, creating a bulge in the front. This tends to give the front a steep slope near its leading edge (figure 9-5). Cold frontal slopes average about 1:80 miles. This means that at 80 miles into the surface position of the front, the frontal boundary is about one mile above the ground.

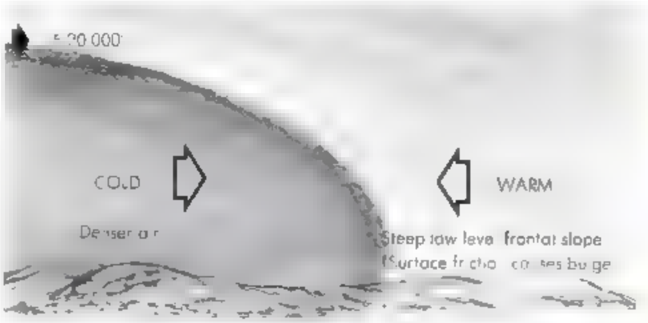


Figure 9-5. Fast-Moving Cold Front Runs Under Warmer Air.

Cold fronts may be accompanied by very marked weather changes and some of the most hazardous flying weather. Figure 9-6A shows how a cold front is depicted on a surface weather chart. Figure 9-6B shows a cross sectional view of the same front. Note that the vertical dimensions of the front, as shown in figure 9-6C, are exaggerated. The exaggeration of frontal structure with height is maintained in all illustrations for increased clarity.

Cold fronts may be divided into two general types: fast moving and slow moving. In extreme cases, cold fronts have been observed to move with speeds of 60 or more miles per-hour at the surface, but they normally move at less than half this speed. They usually move faster in winter than in summer.

Fast-Moving Cold Fronts

Air is forced upward in the area ahead of the surface position of a rapidly moving cold front (figure 9-7). Therefore, most of the heavy cloudiness and precipitation is located just ahead of the front where the opposing air currents meet. This type of front usually causes very hazardous flying weather.

As mentioned earlier, friction often retards the movement of the front near the surface. This causes its slope to steepen, and a narrower band of weather results. If the warm air-mass is moist and unstable, scattered thunderstorms and showers are likely to develop ahead of the front. A *squall-line* may also form.

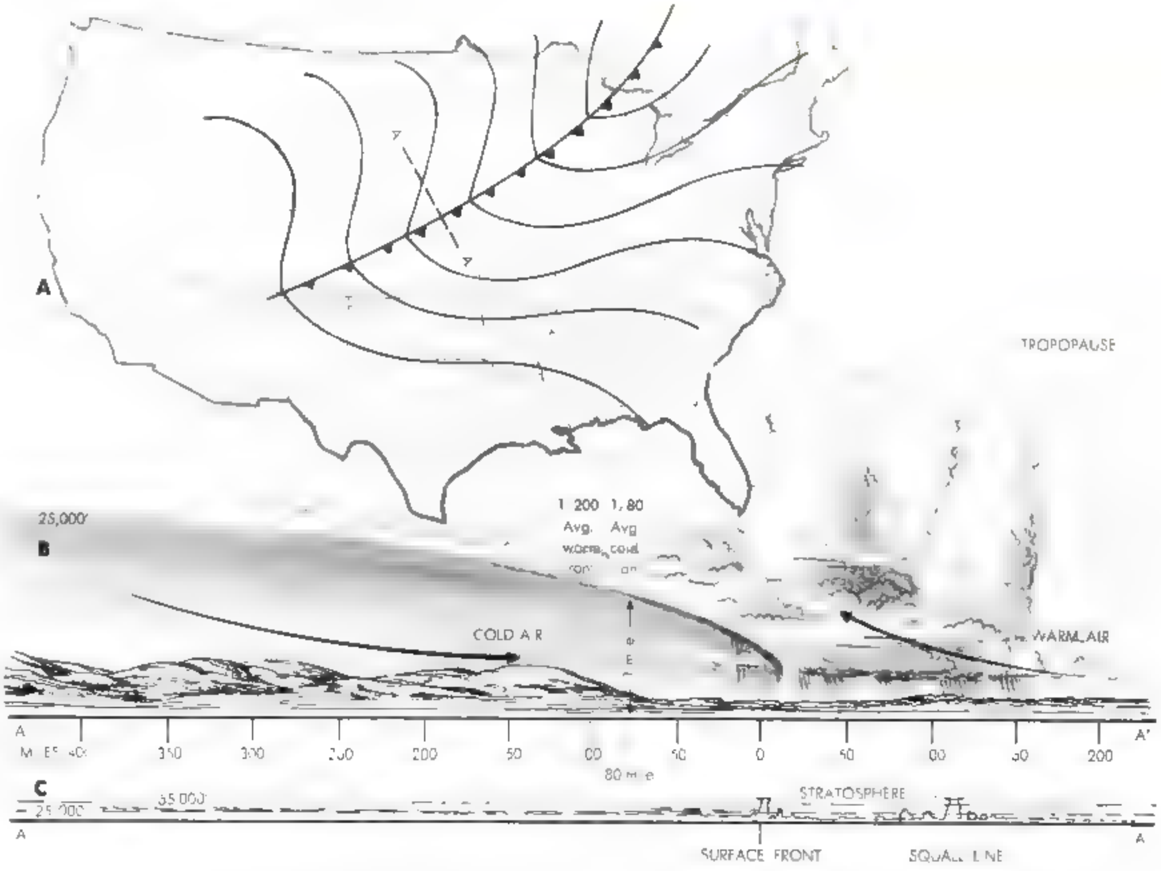


Figure 9-6. Cold Front As Shown On Surface Weather Chart.

This line, as illustrated in figure 9-7, is often characterized by a formidable wall of turbulent clouds building to 40,000 feet or higher. The squall-line sometimes develops between 50 and 200 miles ahead of the front and is roughly parallel to it. Squall lines are accompanied by some of the most turbulent weather known. The weather usually clears rapidly behind a fast moving cold front, with colder temperatures and gusty, turbulent surface winds following its passage.

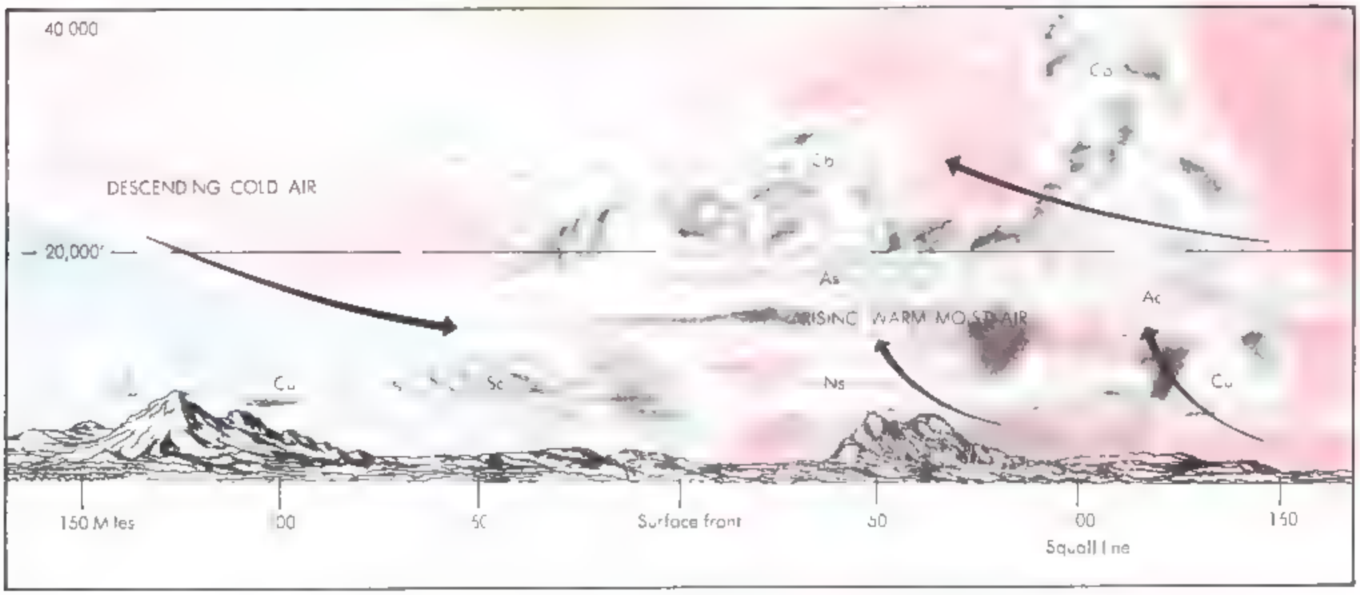


Figure 9-7. Fast-Moving Cold Front And Squall Line.

Slow-Moving Cold Fronts

When the cold front is moving slowly (15 knots or less), there is a general upgliding of the warm air over the frontal surface. This results in a rather broad cloud-pattern in the warm air, with the clouds extending well behind the surface position of the front. Figure 9-8 shows that if the warm air is stable, the clouds are stratiform. Cumuliform clouds and frequently thunderstorms, as shown in figure 9-9, develop if the warm air is moist and unstable. A slow moving cold front or a cold front over a shallow, cold air mass may have a cross section more like that of a warm front.

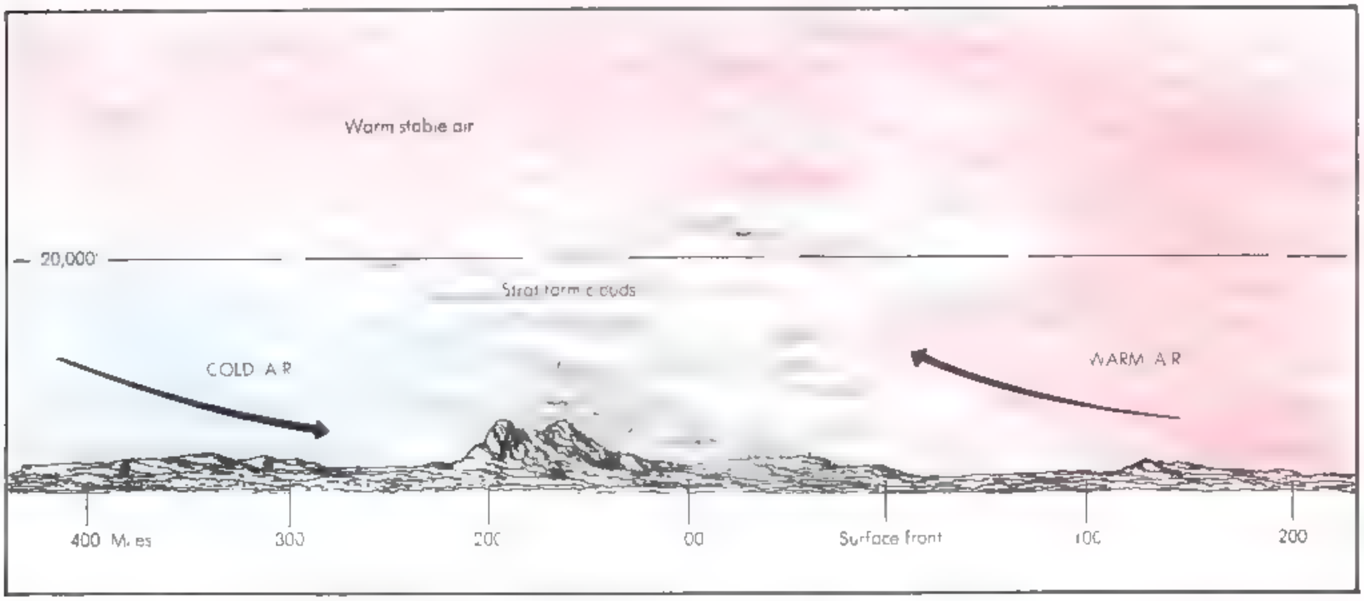


Figure 9-8. Slow-Moving Cold Front And Stable Air.

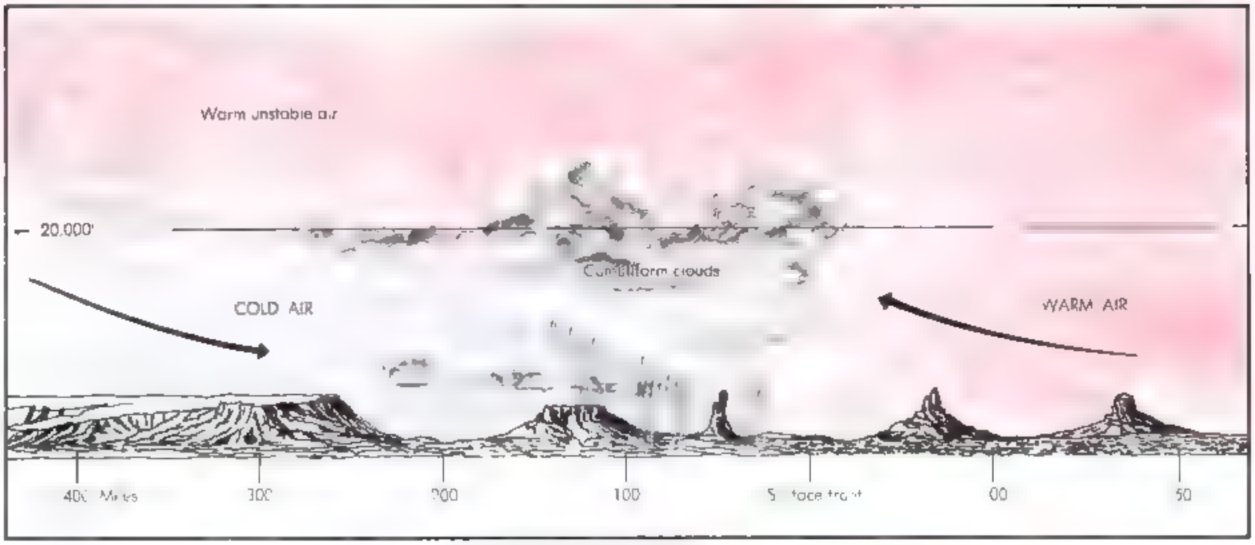


Figure 9-9. Slow-Moving Cold Front And Unstable Air.

Cold Front Weather Hazards

The chief hazards to aircraft flying in the vicinity of a cold front are caused by the cumuliform clouds along the front or the squall-line ahead of the front. These hazards include turbulence (which may be extreme), wind shear, thunderstorms, lightning, heavy rain showers, hail, icing, and possibly tornadoes. Another hazard is the strong, variable, gusty low-level winds (wind shear) at the surface and around and under the thunderstorms.

WARM FRONTS

The edge of an advancing warm air-mass is called a *warm front;* that is, warmer air is overtaking and replacing colder air. Since the cold air is more dense than the warm air, the cold air is slow to retreat in advance of the overriding warm air. This produces a warm frontal slope that is more gradual than the cold frontal slope. Warm frontal slopes usually average about 1:200 miles (figure 9-10).

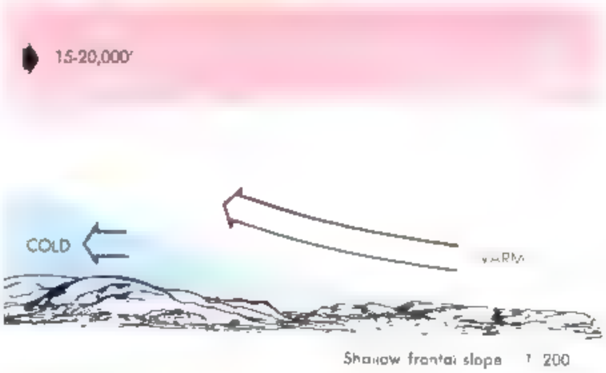


Figure 9-10. Warm Front Runs Up Over Retreating, Slow-Moving Cold Front.

If the advancing warm air is moist and stable, stratiform clouds develop. The sequence of cloud types encountered when flying into an advancing front, as shown in figure 9-11, is cirrus, cirrostratus, altostratus, and nimbostratus. Precipitation increases gradually with the approach of this type of warm front and usually continues until it passes

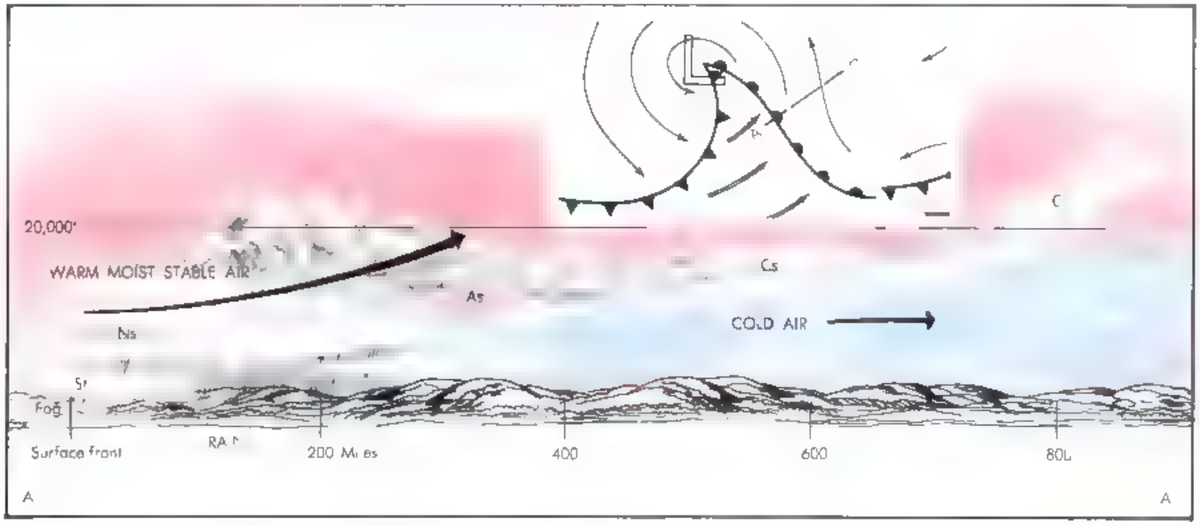


Figure 9-11. Warm Front And Moist Stable Air.

If the advancing warm air is moist and unstable, as shown in figure 9-12, altocumulus and cumulonimbus clouds, and frequently thunderstorms, will be embedded in the cloud masses which normally accompany the warm front. The presence of these thunderstorms is often unknown to the aircrew until the thunderstorm is encountered. Precipitation in advance of the front is usually showery with this condition.

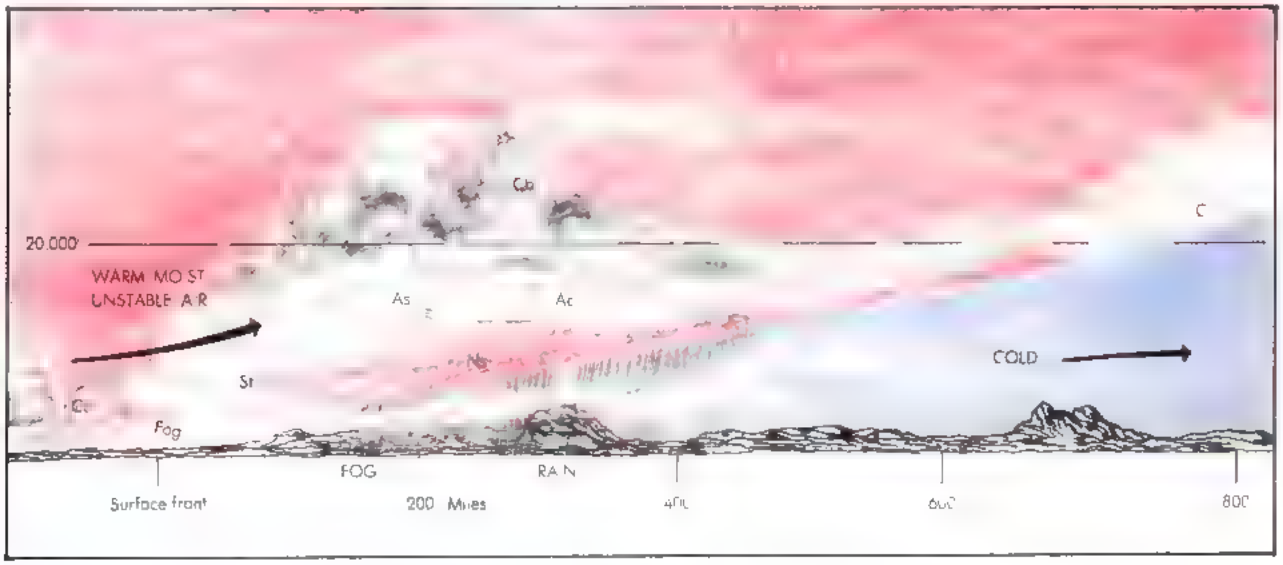


Figure 9-12. Warm Front And Moist Unstable Air.

Warm Front Weather Hazards

The widespread precipitation area ahead of a warm front often causes low stratus and fog to form. In this case, the precipitation raises the humidity of the cold air to saturation. This may produce low ceilings and poor visibility over thousands of square miles. The frontal zone itself may have extremely low ceilings and near-zero visibilities over a wide area. If the cold air has below-freezing temperatures, the precipitation may take the form of freezing rain or ice pellets. Thunderstorms during the warm months of the year and severe icing during the winter are further hazards. Low-level wind shear can be a very significant problem and can last six hours or more at a location prior to warm frontal passage

STATIONARY FRONTS

Sometimes the opposing forces exerted by adjacent air masses of different densities are such that the frontal surface between them shows little or no movement. In such cases, it is usually found that the surface winds tend to blow parallel to the front rather than against and/or away from it. Since neither air mass is replacing the other, as shown in the surface weather chart in figure 9-13, the front is called a *stationary front*.

Although there is no movement of the surface position of the true stationary front, an upglide of air can occur along the frontal slope. The angle of this flow of air in relation to the surface position of the front, and the strength of the upgliding wind, control the inclination of the frontal slope. Fronts moving less than 5 knots are called either *quasi-stationary* or *stationary*.

The weather conditions occurring with a stationary front are similar to those found with a warm front but are usually less intense. An annoying feature of the stationary front and its weather pattern is that it may persist and hamper flights in one area for several days.

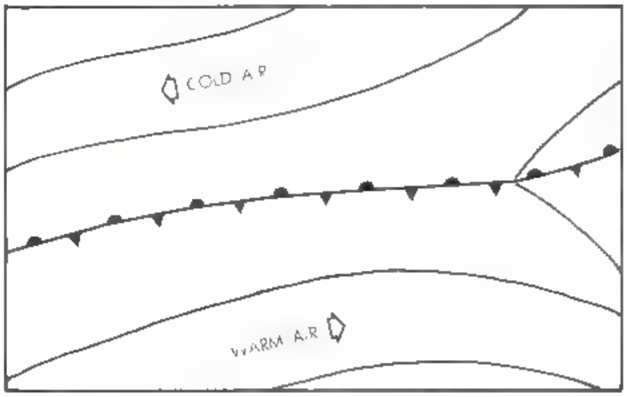


Figure 9-13. Stationary Front As Shown On Surface Weather Chart.

FRONTAL WAVES AND OCCLUSIONS

Frontal waves are primarily the result of the interaction of two air masses, they usually form on slow-moving cold fronts or stationary fronts

In the initial stage of figure 9-14, the winds on both sides of the front are blowing parallel to it (A). Small disturbances in this pattern of winds, as well as perhaps uneven local heating and irregular terrain, may start a wave-like bend in the front (B). These disturbances often are not obvious on the weather chart. If this tendency persists and the wave increases in size, a counterclockwise (cyclonic) circulation is set up. One section of the front begins to move as a warm front, while the section next to it begins to move as a cold front (C). This deformation is called a *frontal wave*.

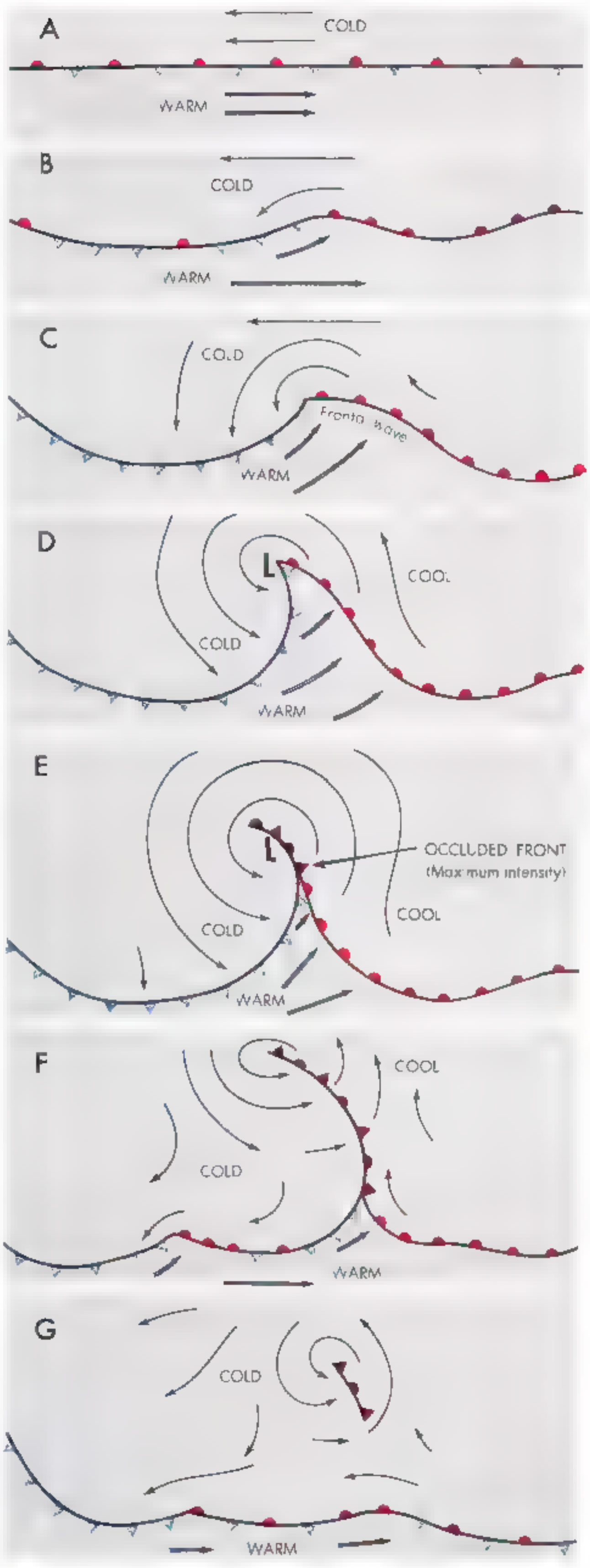


Figure 9-14. Frontal Wave And Occlusion.

The pressure at the peak of the frontal wave falls, and a low pressure center is formed. The cyclonic circulation becomes stronger, and the winds begin to move the fronts. The cold front moves faster than the warm front (D). When the cold front catches up with the warm front, the two of them occlude (close together). The result is called an *occlusion* (E). This is the time of maximum intensity for the wave cyclone. Note that the symbol depicting the occlusion is a combination of the symbols for the warm and cold fronts.

As the occlusion continues to grow in length, the low pressure area weakens and the frontal movement slows down (F). Sometimes a new frontal wave may, at this point, begin to form on the long westward-trailing portion of the cold front. In the final stage, the two fronts have become a single stationary front again. The low center with its remnant of the occlusion is disappearing (G).

Figure 9-15 shows how one section of a frontal wave moves toward the cold air as a warm front, while an adjacent section moves toward the warm air as a cold front. Two vertical cross-sections of the frontal wave, one to the north of the surface position of the wave and the other across the cold and warm fronts of the wave, are shown also in figure 9-15.

Weather Associated with an Occlusion

Since occlusions are the result of one frontal system overtaking a previously formed frontal system, occlusions combine the weather of both a warm and cold front into one extensive system. A line of showers and thunderstorms typical of a cold front merges with the low ceilings of the warm front. Precipitation and low visibilities are widespread over a large area on either side of the surface position of the occlusion. In addition, strong winds will occur around an intense low at the northern end of the occlusion. Aircrews should be aware that weather conditions change rapidly in occlusions and are usually most severe during the initial stages of development.

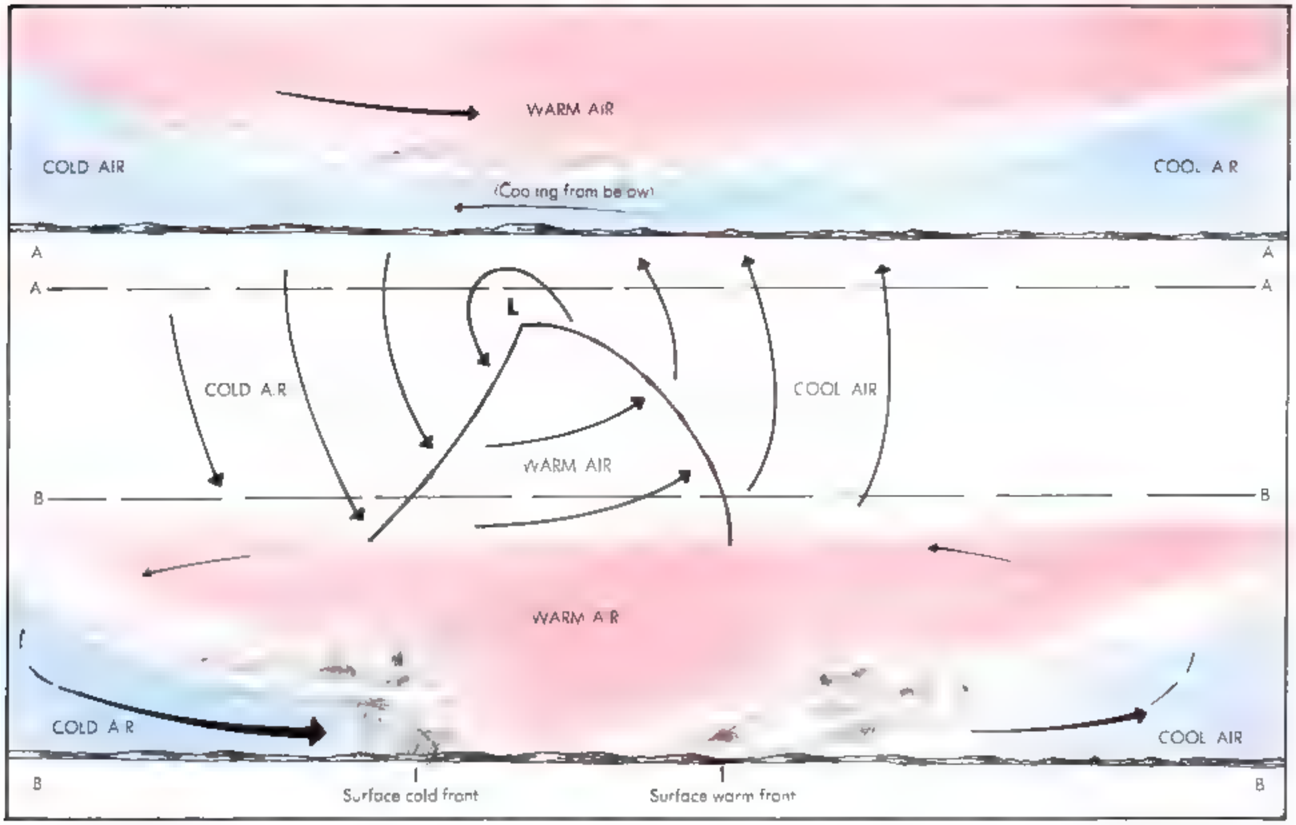


Figure 9-15. Vertical Cross-Section Of A Frontal Wave.

CHAPTER 10

TURBULENCE

A turbulent atmosphere is one in which air currents vary greatly over short distances. These currents range from rather mild eddies to strong currents of relatively large dimensions. The effect of turbulence can range from a few annoying bumps to severe jolts capable of structurally damaging the aircraft and injuring crew and passengers. While severe turbulence is a rare event, light and moderate turbulences occur frequently at virtually all flight levels and during all seasons.

A knowledge of the location and causes of turbulence is helpful in minimizing its effects or avoiding it altogether. In this chapter we will discuss the following types of turbulence:

Convective Turbulence: Caused by alternating currents of warm air rising and cooler air descending.

Mechanical Turbulence: Caused by wind flowing over irregular terrain or obstructions, or by a marked change of wind speed and or direction in a short distance.

Mountain Wave Turbulence: Caused when stable air blows perpendicular across the top of a mountain range

High Altitude Turbulence Consisting of the jet stream and clear air turbulence (CAT)

Vortex Wake Turbulence: Generated by every aircraft and helicopter in flight.

CONVECTIVE TURBULENCE

Convective currents are a common cause of turbulence, especially at low altitudes. These currents are localized vertical air movements, both *ascending* and *descending.* For every rising current, there is a compensating downward current. The downward currents frequently occur over a broad area, and therefore they usually have a slower vertical speed than the rising currents.

Convective currents are most active on warm, summer afternoons when the winds are light, since strong winds break up these currents. Heated air at the surface creates a shallow, unstable layer, and the warm air rises. Convection increases in strength and to greater heights as surface heating increases. Barren surfaces such as sandy or rocky wasteland and plowed fields become hotter than open water or ground covered by vegetation (figure 10-1). Thus, air at or near the surface heats unevenly. Because of this, the strength of the convective currents can vary considerably within short distances. Figure 10-2 and 10-3 illustrate this effect on an aircraft approaching an airport for landing. The rough air resulting from convective currents is referred to as *convective turbulence*

As air moves upward, it cools by expansion. A convective current continues upward until it reaches a level where its temperature cools to the same as that of the surrounding air. If it cools to saturation, a cloud forms. Aircrews should associate thermal turbulence with cumulus and cumulonimbus clouds. Turbulence may be severe beneath or in the clouds, while air generally is smooth above the clouds (figure 10-4).

Aircrews should also be aware that when air is too dry for cumulus clouds to form, convective currents can still be active. Crew members will have little indication of these currents until they encounter turbulence

Aircraft reaction to turbulence varies not only with the intensity of the convective currents, but also with aircraft characteristics such as airspeed, aircraft weight and design, wing loading, and pilot technique. At higher aircraft speeds, turbulence will seem more severe because of the more rapid changes in the vertical motion of the aircraft. Therefore, to minimize the effect of convective turbulence, tighten your seat belt and shoulder harness and fly the turbulence airspeed recommended by your aircraft performance manual.

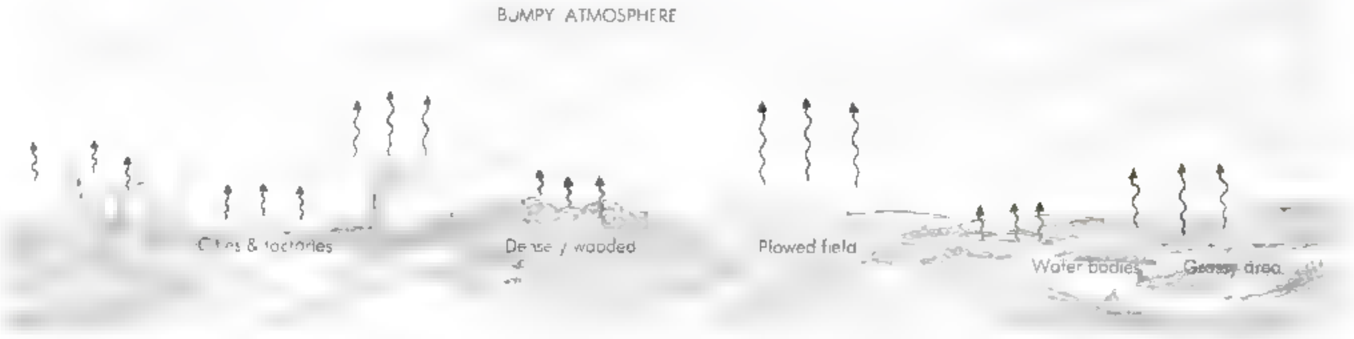


Figure 10-1. Strength Of Convective Currents Vary With Composition Of Surface.

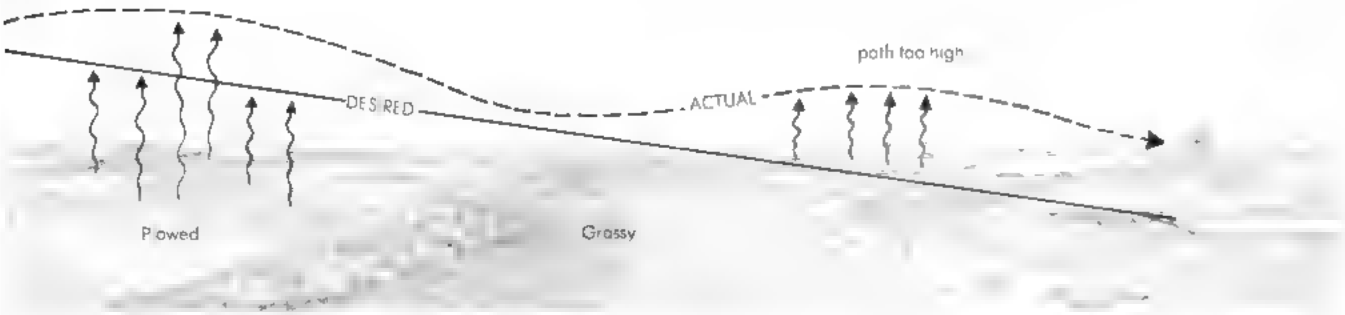


Figure 10-2. Updrafts May Cause Pilots To Overshoot.

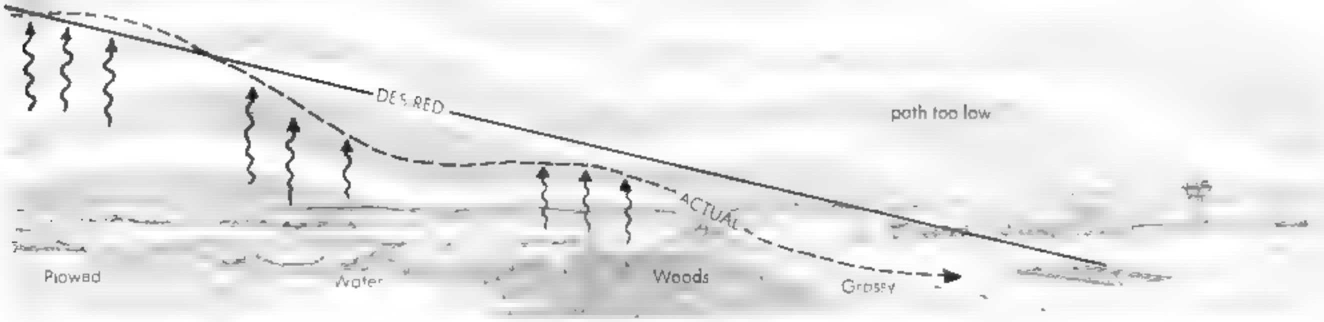


Figure 10-3. Downdrafts May Cause Pilots To Undershoot.

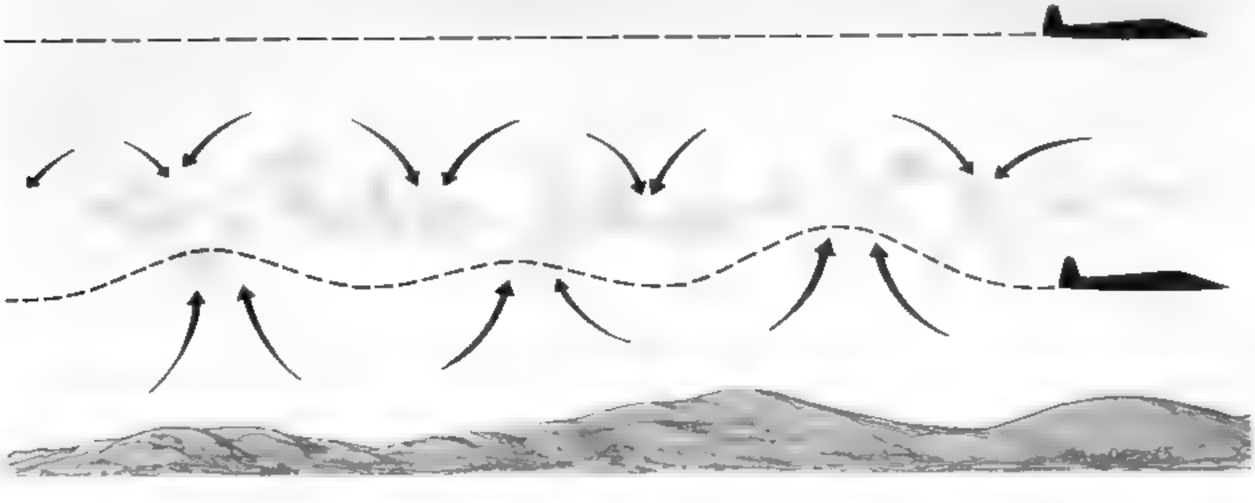


Figure 10-4. Avoid Convective Currents By Flying Above Cumulus Clouds.

MECHANICAL TURBULENCE

Turbulence occurring when air near the surface of the earth flows over rough terrain or other obstructions is a mechanical process. Where obstacles such as trees, buildings, and hills block its path, the normal wind flow is transformed into a complicated snarl of eddies (figure 10-5) These eddies tend to be carried along the general wind flow, their size and extent affecting the flying characteristics of aircraft.

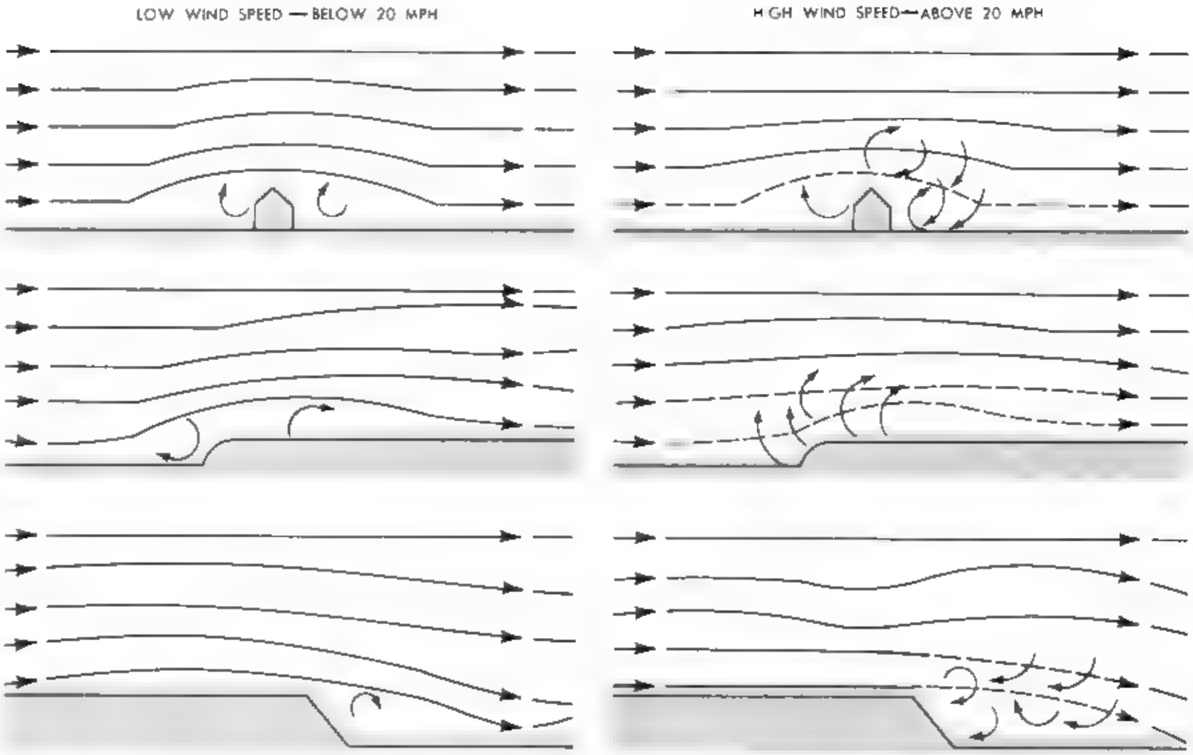


Figure 10-5. Surface Obstructions Cause Eddies And Other Irregular Wind Movements.

The degree of mechanical turbulence depends on the roughness of the terrain or obstructions, the wind speed, and the stability of the air mass. The higher the wind speed and/or the rougher the surface, the greater is the turbulence intensity. Unstable air allows larger eddies to form than those in stable air; but the instability breaks up the eddies quickly, while in stable air they dissipate slowly.

Variability of wind near the ground is an extremely important consideration during takeoff and landing, especially for light aircraft. Gusty winds have caused many aircraft accidents, as shown in figure 10-6, and aircrews landing at airports where large hangars or other buildings are located near the runways should be alert for turbulent eddies. If the wind is light, eddies tend to remain as rotating pockets of air near the windward and leeward sides of the buildings. But, if the wind speed exceeds about 20 knots, the flow may be broken up into irregular eddies which are carried a sufficient distance downstream to create a hazard in the landing area.

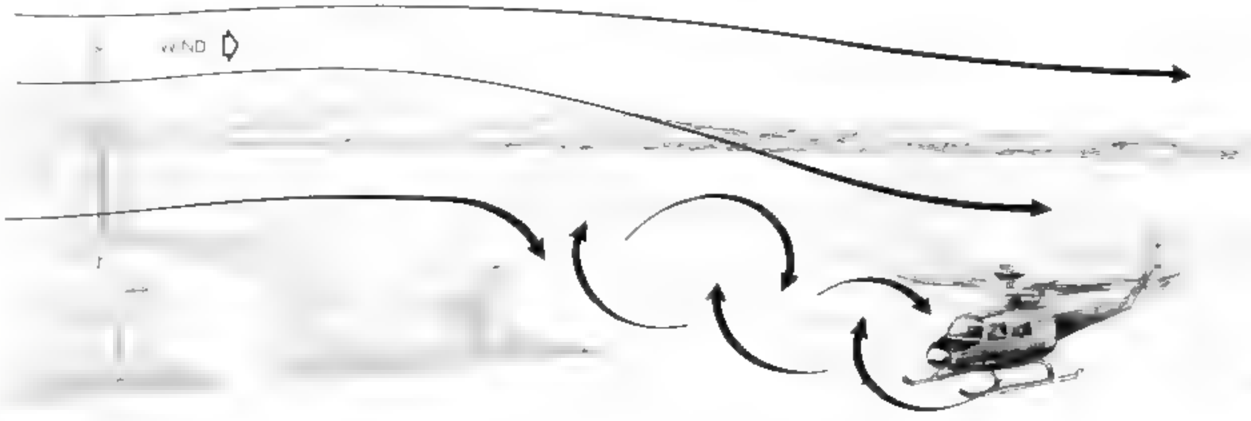


Figure 10-6. Buildings Near Landing Area May Cause Turbulence.

When winds blow across rugged hills or mountains, the resulting turbulence may increase as the wind speed increases. Extreme caution is necessary when crossing mountain ranges under strong wind conditions. Severe downdrafts can be expected on the lee side as illustrated in figure 10-7. These downdrafts can be dangerous and can place an aircraft in a position from which it might not be able to recover. Aircrews should allow for this condition when approaching mountain ridges against the wind. If the wind is strong and the ridges pronounced, pilots should climb aircraft to a crossing altitude several thousand feet higher than the highest obstruction.

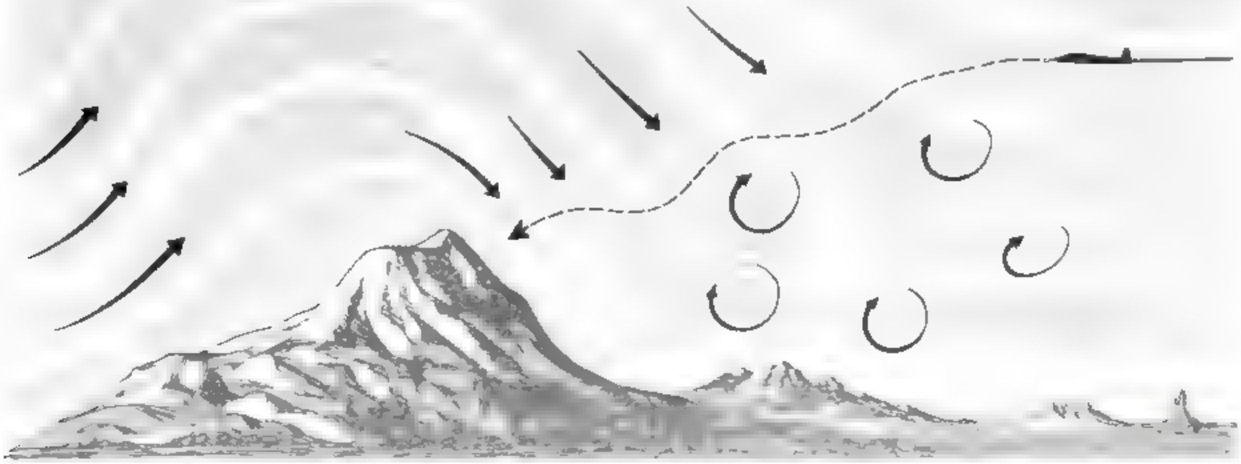


Figure 10-7. Wind Flow Over Mountain Ranges Produces Turbulence.

It is important to climb to the crossing altitude well before reaching the mountains to avoid having to climb (or, what is worse, trying unsuccessfully to climb) in a persistent downdraft. Attempting to cross at a lower altitude will also subject the aircraft to much greater turbulence and sudden crosswinds caused by winds blowing suddenly parallel to the valley instead of the prevailing direction.

When the wind blows across a valley or canyon, a downdraft will occur on the lee side, while an updraft will result on the windward side (figure 10-8). If flight through the canyon is required, the safest path is to fly near to the side of the pass or canyon which affords an upslope wind, since additional lift is provided.

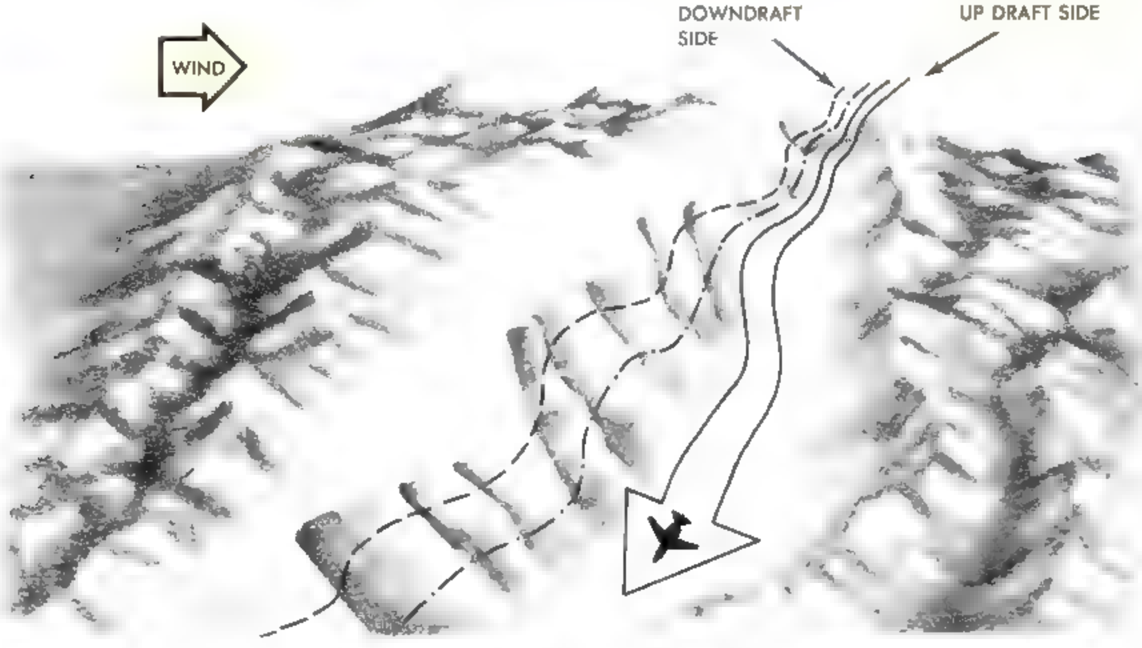


Figure 10-8. In A Valley Or Canyon, Safest Path Is On Upslope Wind Side.

If the wind blows across a narrow canyon or gorge, it will veer down into the canyon (figure 10-9). Turbulence will be found near the middle and downwind side of the canyon or gorge. Aircrews must avoid the downwind side of *narrow* canyons, because a rate-of-descent of such magnitude may be established that the aircraft may continue descending and crash.

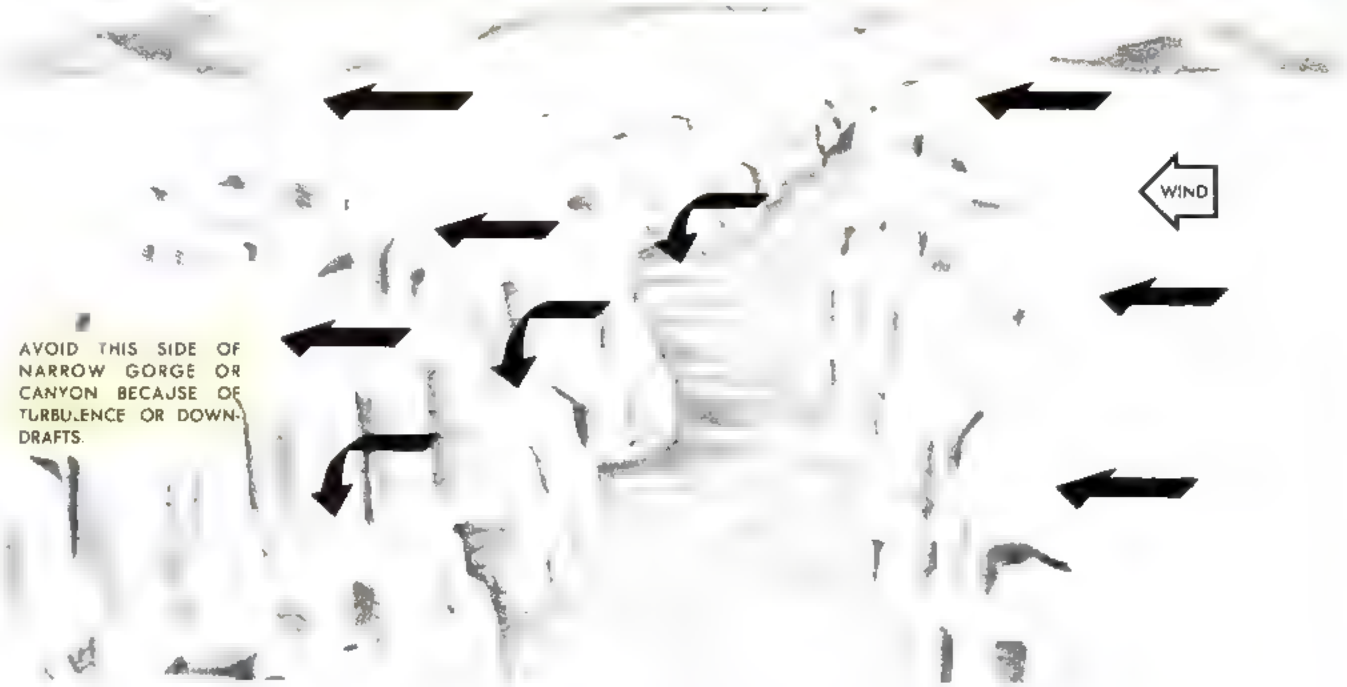

WIND
AVOID THIS SIDE OF NARROW GORGE OR CANYON BECAUSE OF TURBULENCE OR DOWNDRAFTS.

Figure 10-9. Avoid Downwind Side of Narrow Gorge.

Flying mountain passes and valleys is not a safe procedure during high winds. The mountains funnel winds into passes and valleys, thus increasing wind speed and intensifying turbulence. If winds at mountain top level are strong, fly high or fly around the valley.

MOUNTAIN WAVE TURBULENCE

When *stable* air blows across a mountain range, a phenomenon known as a mountain wave may occur. A wave condition usually develops when the component of wind flowing perpendicular to the top of the mountain exceeds 25 knots Although the actual wind direction can vary somewhat and still cause a wave, the strongest waves occur with a strong, perpendicular flow. The waves, which resemble ripples formed downstream from a rock submerged in a swiftly flowing river, remain nearly stationary while the wind blows through them. The characteristics of a typical mountain wave are shown in figure 10-10. Waves such as these are commonly associated with high mountain ranges, but it has been established that any mountain range or ridge line with a crest of 300 feet or higher is capable of producing wave phenomena.

The most dangerous features of the mountain wave are the extreme turbulence and very high velocity updrafts and downdrafts on the lee side of the mountain range. Associated areas of updrafts and downdrafts may extend as high as 70,000 feet and as far as 300 miles downstream from the mountain range (figure 10-11). The amplitude and intensity of the waves decrease the further downstream they occur.

While clouds are generally present to forewarn the aircrew of mountain wave activity, it is possible for wave action to take place when the air is too dry to form clouds. However, characteristic cloud forms, peculiar to wave action, still provide the best means for identifying the presence of the wave The clouds usually indicating wave action are cap clouds, rotor clouds, and lenticular clouds.

The *cap cloud* is a low hanging cloud with its base near the mountain top and at times obscuring the mountain peak. Most of the cloud is on the windward side, while on the leeward side the cloud looks like a wall hanging over the edge with fingers pointing down the slope.

The *rotor cloud* gives a visible appearance of turbulence. The rotor cloud looks like a line of cumulus clouds parallel to the ridge line (figure 10-12). The cloud is usually stationary and is constantly forming and dissipating on the lee side with updrafts and downdrafts of up to 5,000 feet per minute. The rotation of the cloud may not be apparent to the crew member The most dangerous features of mountain waves are the turbulence in and below the rotor clouds and the downdrafts just to the lee of the mountain ridges and to the lee of the rotor clouds.

The *lenticular cloud* is lens-shaped and is probably the most frequent cloud associated with mountain waves (figure 10-13). The lenticular clouds, like the rotor, are stationary, constantly forming in bands parallel to the mountain at fairly regular-spaced intervals on the leeward side.

Lenticular clouds are usually found above 20,000 feet and sometimes are piled upon massive layers. The lenticulars are usually turbulent regardless if they are smooth or ragged in appearance.

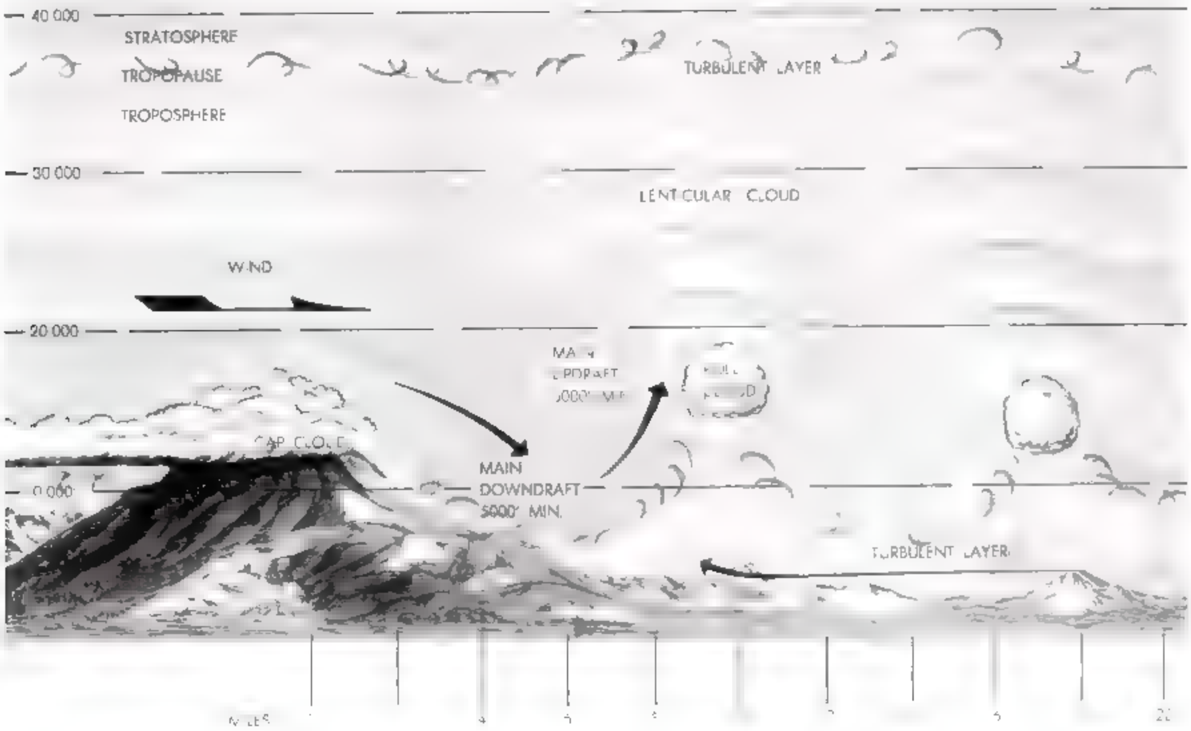


Figure 10-10. Typical Cloud Formation, Main Downdraft and Updraft In Mountain Wave.

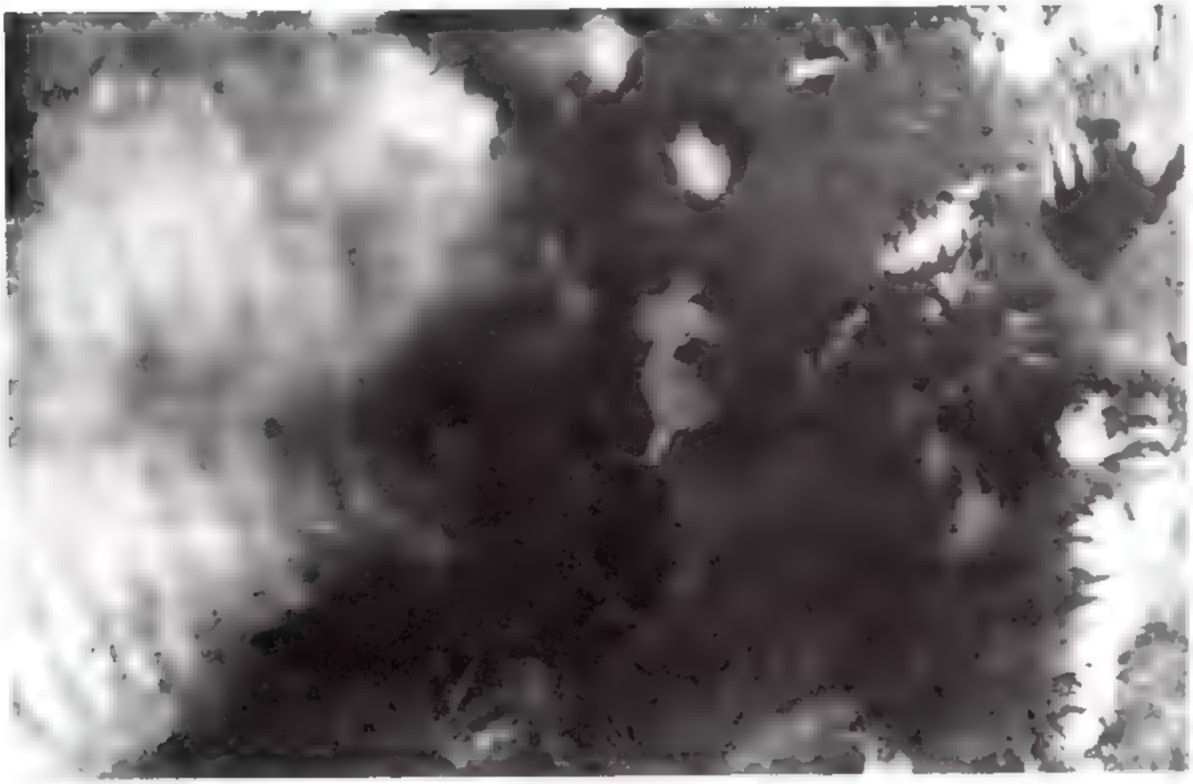


Figure 10-11. Mountain Waves Photographed From A Manned Spacecraft.

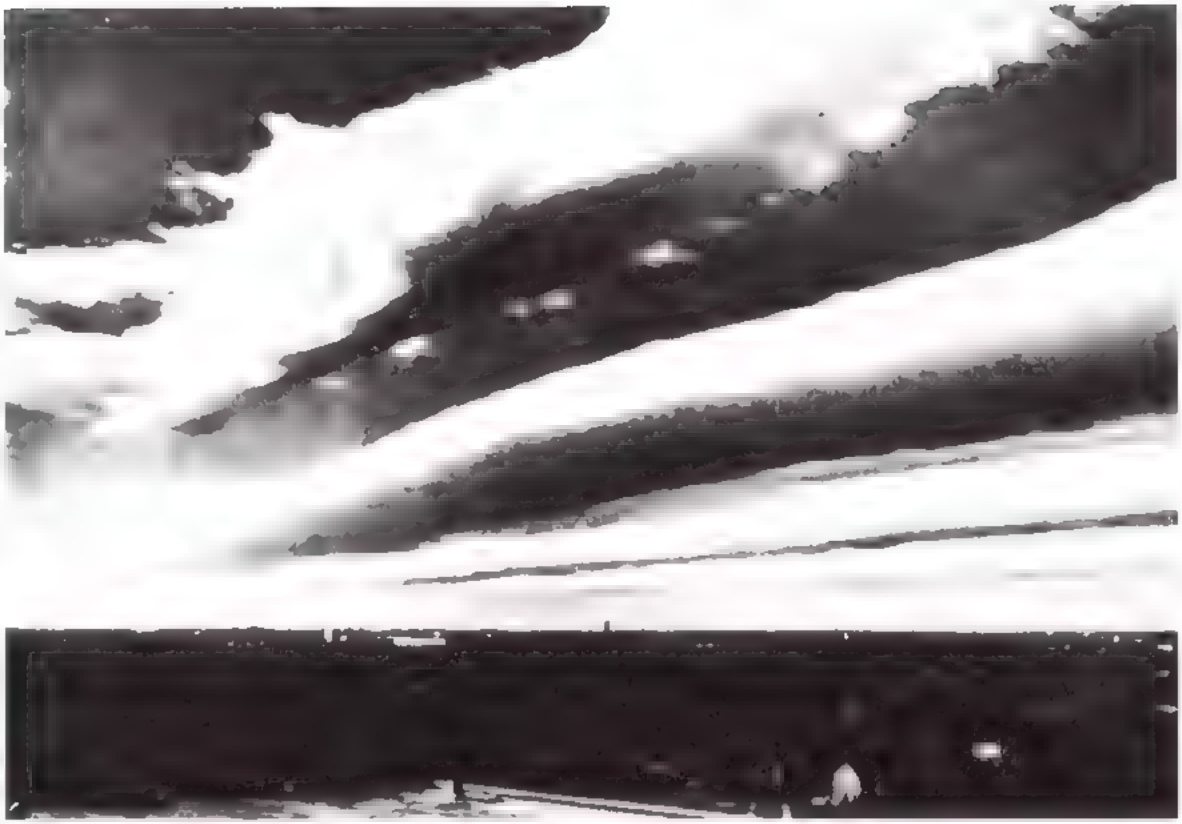


Figure 10-12. Rotor Clouds.

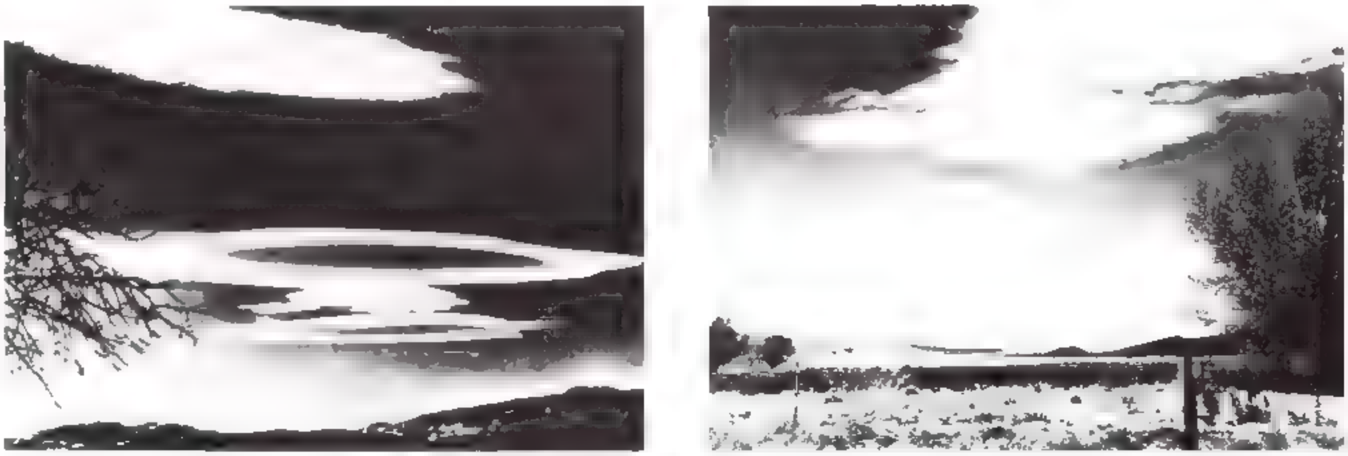


Figure 10-13. Standing Lenticular Clouds Associated With A Mountain Wave.

Barometric pressure is considerably lowered in the mountain wave because of the venturi effect of high winds over an obstruction. Therefore, significant pressure altimeter errors are associated with the mountain wave The maximum error can be as high as 2,500 feet if a strong wave is in progress. Therefore, the altimeter may indicate as much as 2,500 feet higher than the actual aircraft altitude

Aircrews should avoid flight into areas of suspected mountain wave conditions. If flight into the area must be made, the following safeguards should be followed·

- Avoid the cap, rotor, and lenticular clouds since they contain intense turbulence and strong updrafts and downdrafts.
- As a minimum, fly at a level which is at least 50 percent higher than the height of the mountain range. This procedure will not keep the aircraft out of turbulence, but provides a margin of safety if a strong downdraft is encountered
- Approach the mountain range at a 45° angle, so that a quick turn can be made away from the ridge if a severe downdraft is encountered
- Suspect pressure altimeter errors. *Altimeters may indicate 2,500 feet higher than actual altitude*
- Penetrate turbulent areas at airspeeds recommended for your aircraft.

HIGH ALTITUDE TURBULENCE

The Tropopause

The tropopause is often a region of turbulence because of the marked variations in vertical motions which occur in, at, or below the tropopause. The tropopause is often devoid of clouds so that turbulence encountered there will frequently be classified as clear air turbulence

As we have seen, the tropopause is higher at the equator than at the poles. However, there are generally two breaks in the tropopause - one between the arctic and polar air masses, and one between the polar and tropical air masses. It is where these breaks in the tropopause appear that a very important flight factor can be found - the *jet stream*.

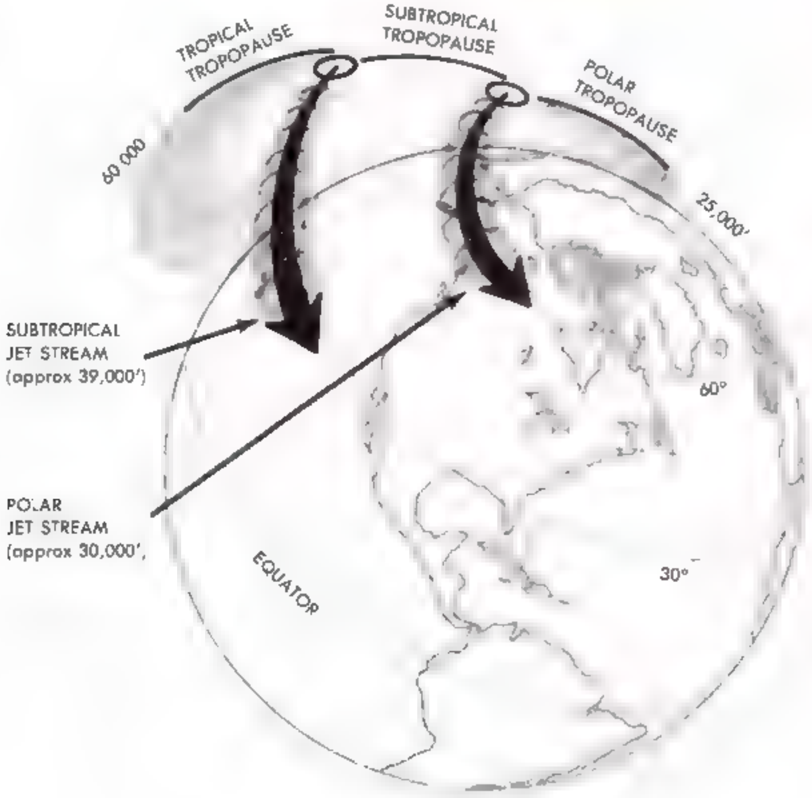


Figure 10-14. Location Of Polar And Subtropical Jet Streams In Relation To Tropopause.

Jet Stream

A jet stream, as illustrated in figure 10-15, is a narrow, shallow band of strong westerly winds of 50 knots or more which meanders vertically and horizontally around the hemisphere in wave-like patterns. Jet streams are characteristic of both the Northern and Southern Hemispheres; however, this discussion will be limited to Northern Hemispheric jet streams

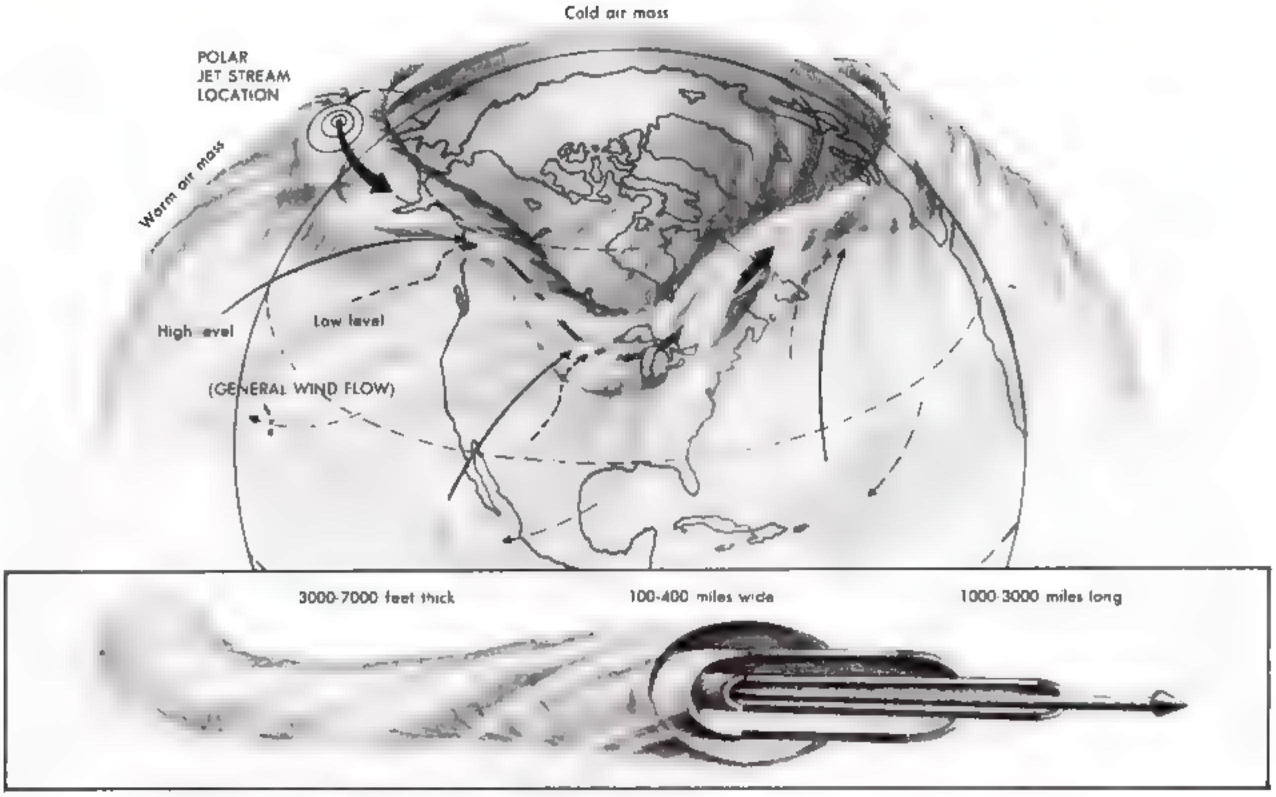


Figure 10-15. The Polar Front Jet Stream.

Wind speeds in the jet stream sometimes may reach 300 knots but generally are between 100 and 150 knots. Since the jet stream is stronger at some places than at others, it rarely encircles the entire hemisphere as a continuous river of wind. More frequently it is found in segments from 1,000 to 3,000 miles in length, 100 to 400 miles in width, and 3,000 to 7,000 feet in depth.

The polar jet stream appears to have a life cycle of formation, intensification, movement, and dissipation related to the polar front. The strength of the jet stream is greater in winter than in summer. The mean position of the polar jet stream shifts south in winter and north in summer with the seasonal migration of the polar front. As the jet stream moves southward, its core rises to a higher altitude, and on the average, its speed increases. The core of strongest winds is generally found between 25,000 feet and 40,000 feet, depending on latitude and season.

In figure 10-16 notice that the highest wind speeds in the polar front jet stream are found about 5,000 feet below the tropical tropopause and near the end of the polar tropopause. Also notice that the rate of decrease of wind speed is much greater on the polar side than on the equatorial side. Therefore, the magnitude of the wind shear is greater on the polar side than on the equatorial side.

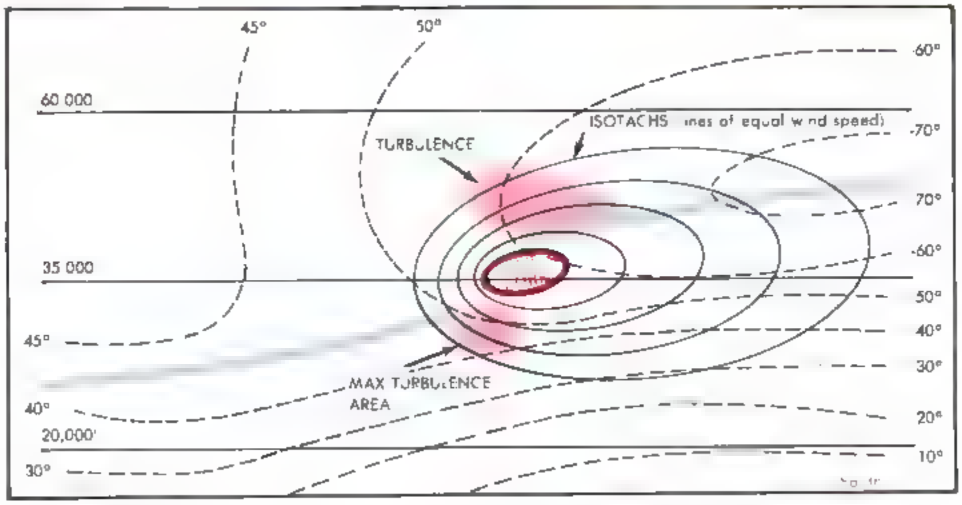


Figure 10-16. Areas Of Probable Turbulence In Jet Stream.

As discussed earlier, the polar front is not a one time thing. One polar front follows another at intervals of a few days or so, and more than one may exist at the same time. Likewise, one polar front jet follows another, and as illustrated in figure 10-17 over Canada, two or more may exist simultaneously. There is hardly a day in the colder months without at least one jet stream, and often two or more, meandering over the United States.

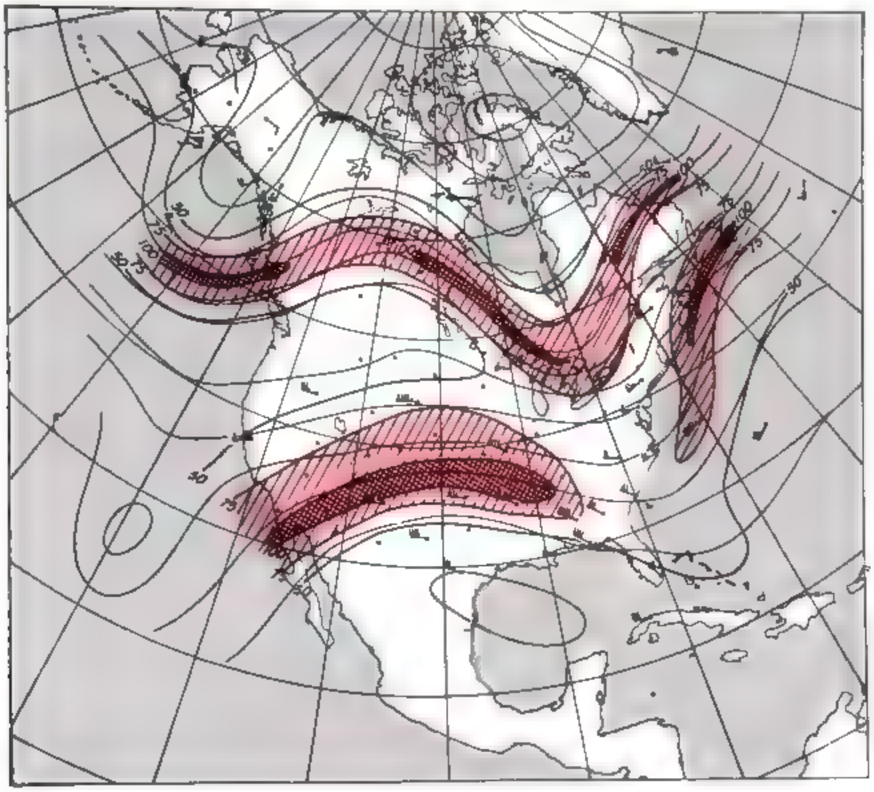


Figure 10-17. Examples Of Multiple Structure Of Jet Stream (Shaded Areas Have Highest Winds).

The existence of jet streams at operational altitudes requires additional aircrew flight planning consideration. The greater headwind component for westbound aircraft will increase fuel consumption and may require additional alternates along the route. Wind shear associated with the jet stream may also cause turbulence, forcing the aircrew to change altitude or course.

Clear Air Turbulence

The term *clear air turbulence* (CAT) is commonly used to denote the rough, washboard-like bumpiness which sometimes buffets an airplane in a cloudless sky But CAT is not restricted to cloud free air It occurs in cirrus clouds and haze layers with no visual warnings Studies show that only about 75 per cent of all CAT encounters are in clear air.

Clear air turbulence differs from the convective turbulence, such as found in thunderstorms and the mechanical turbulences near the surface, in that it is more rhythmic in nature rather than random. CAT is usually found above 15,000 feet, outside of cumuliform cloudiness, in association with a marked change in wind speed either with height (vertical wind shear) and or in the horizontal (horizontal wind shear) Not all CAT is associated with jet streams, but the most likely location of CAT, and especially the more severe cases, is considered to be with jet stream situations as shown in figure 10-16. Strong wind shears are found in these areas

If jet stream turbulence is encountered with direct tail winds or head winds, change flight level or course since these turbulent areas are elongated with the wind but are shallow and narrow. Jet stream clear air turbulence often occurs in patches averaging about 2,000 feet deep, 20 miles wide, and 50 miles long.

If jet stream turbulence is encountered in a crosswind, it is not so important to change course or flight level. However, if it is desired to traverse the CAT area more quickly, either climb or descend after watching the temperature gage for a minute or two. *If the temperature is rising - climb; if it is falling - descend* This maneuver will prevent following the sloping tropopause or frontal surface and thereby staying in the turbulent area. If the temperature remains the same, you can either climb or descend.

The occurrence of CAT can extend to very high levels and can be associated with other windflow patterns which produce shears. A sharp trough aloft, especially one moving at a speed greater than 20 knots, can have clear air turbulence in or near the trough, even though the wind speeds can be rather low as compared with the speeds near the jet stream. However, the winds on opposite sides of the trough can have a difference of 90 degrees or more in direction (figure 10-18A). CAT can occur in the circulation around a closed low aloft, particularly if the flow is merging or splitting (figure 10-18B) and is to the northeast of a cutoff low aloft (figure 10-18C).

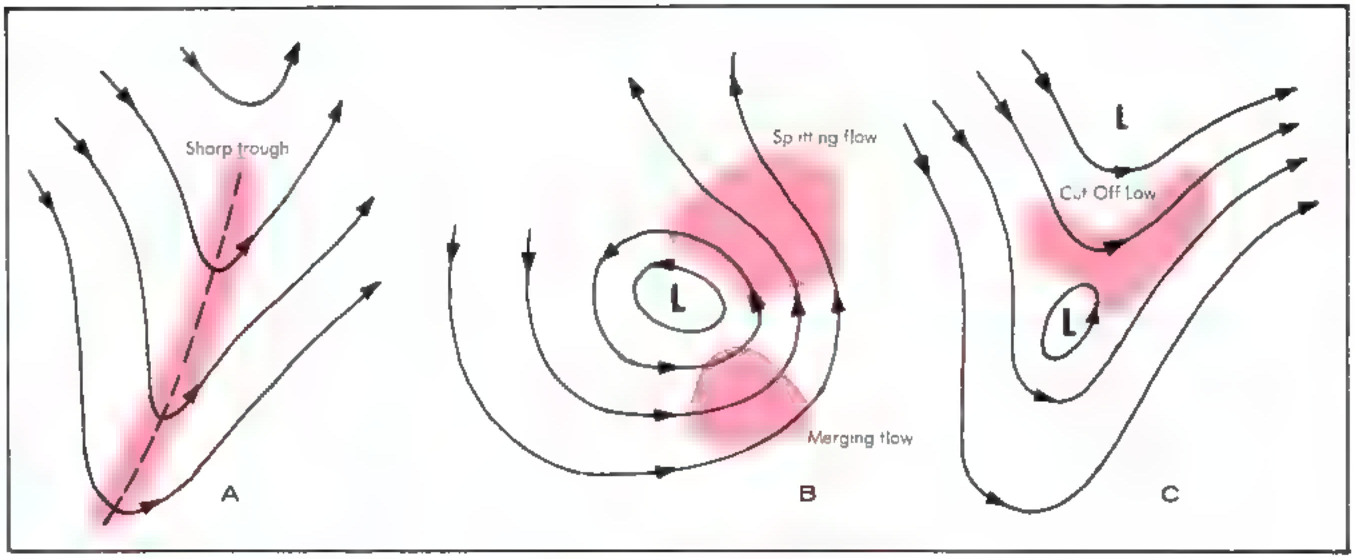


Figure 10-18. Wind Patterns Associated With High-Level CAT.

When anticipating or encountering CAT, fly the turbulence-penetration air speed recommended in the flight manual for your aircraft. Ordinarily, this will reduce the effect of turbulence. However, if the intensity of the turbulence requires further action, climb, descend, and/or change course to exit the turbulent zone, using the information provided by the weather forecaster during preflight or pilot-to-metro facilities. Make very gradual climbs, descents, and turns to minimize additional stress on the aircraft. Finally, always make inflight reports of CAT or other turbulence encounters

VORTEX WAKE TURBULENCE

Every aircraft in flight generates a pair of counter-rotating vortices trailing from the wing tips (figure 10-19). Many large jets generate vortices which exceed the roll capability of some aircraft. The strength of the vortex is governed primarily by the weight, speed, and shape of the wing of the generating aircraft. The basic factor is weight, and the vortex strength increases with increases in weight and span loading. The greatest vortex strength occurs when the generating aircraft is HEAVY-CLEAN-SLOW. Vortex tangential velocities have been recorded up to 130 knots.

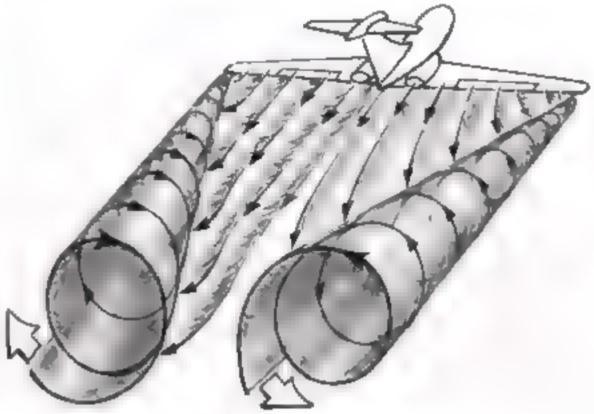


Figure 10-19. Counter-Rotating Vortices.

A serious wake encounter could result in structural damage The primary hazard is loss of control because of induced roll (figure 10-20). The capability of counteracting this roll depends on the span and counter-control responsiveness of the encountering aircraft. Where the wing span and ailerons of larger aircraft extend beyond the vortex, counter-control is usually effective and the induced roll is minimal. The significant factor in induced roll is the *relative span* of the encountering aircraft (figure 10-21)

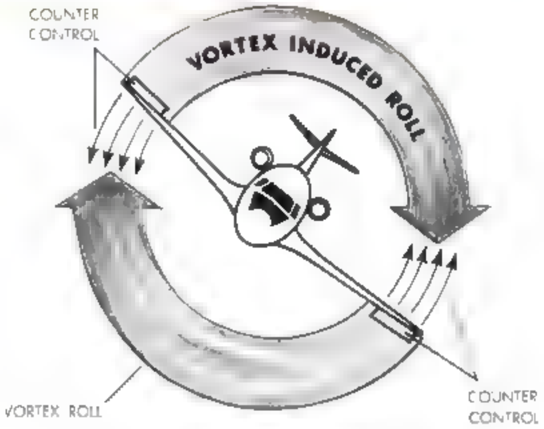


Figure 10-20. Induced Roll.

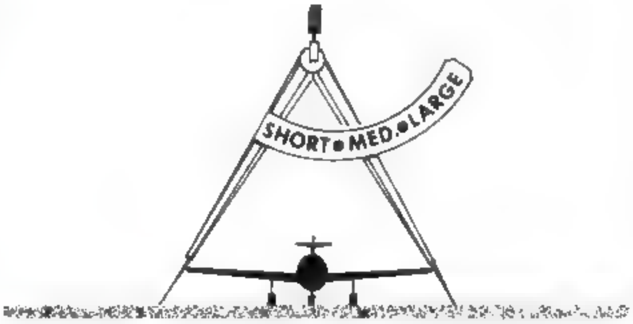


Figure 10-21. Relative Span.

Trailing vortex wakes have certain characteristics which the aircrew can use to visualize their location and avoid them.

- Vortex generation starts with rotation when the nose-wheel lifts off and ends when the nose-wheel touches down on landing (figure 10-22).

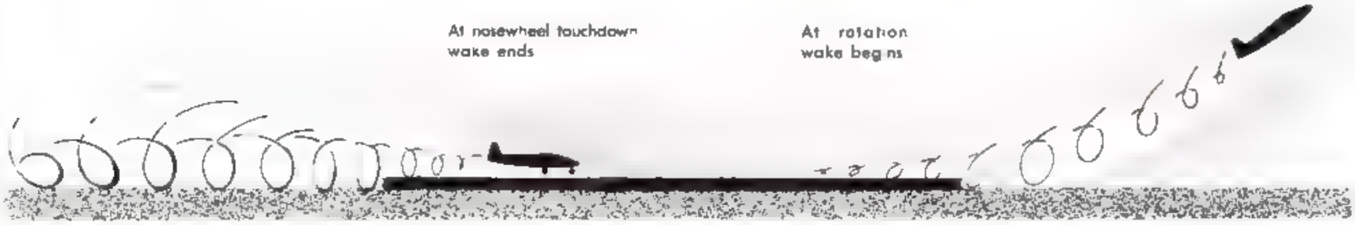


Figure 10-22. Vortex Generation.

- Vortex circulation is outward, upward, and around the wing tip. Core sizes range from 25 to 50 feet and stay close together until dissipation (figure 10-23)

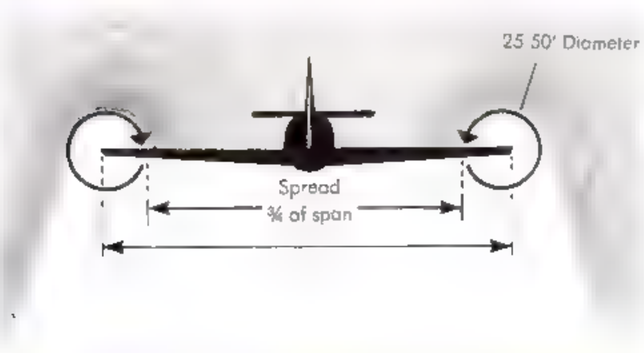


Figure 10-23. Vortex Circulation.

- Vortices sink immediately at a rate of 400 to 500 feet-per-minute and level off 800 to 900 feet below the flight path (figure 10-24). Pilots should fly at or above a preceding aircraft's flight path.
- When vortices sink into ground effect, they move laterally on the ground at a speed of about 5 knots (figure 10-25). Cross-winds will influence the lateral movement (figure 10-26). Aircrews should be alert to heavy jets upwind. Tail-wind conditions can move the vortices forward of the touchdown zone (figure 10-27)
- Vortices persist longer during inversions. When such conditions exist, aircrews should request additional aircraft separation

Helicopter-hovering can generate a downwash from its main rotor(s) similar to the prop-blast of conventional aircraft. In forward flight, this energy is transformed into a pair of trailing vortices similar to wing-tip vortices (figure 10-28). Pilots of small aircraft and helicopters should avoid both the vortices and downwash of a heavy helicopter.

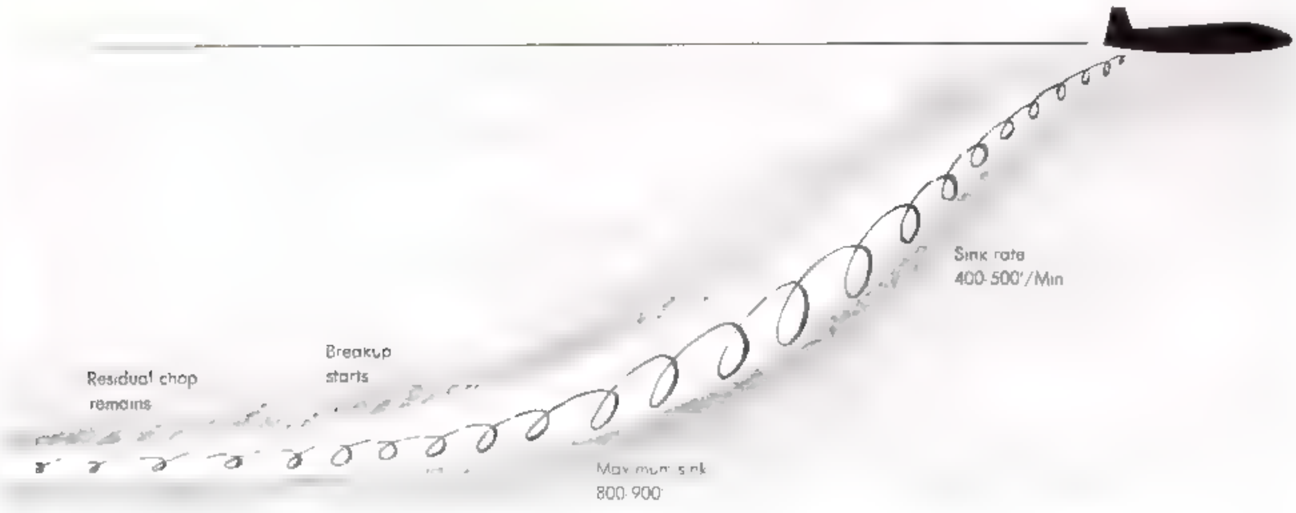


Figure 10-24. Vortex Sink Rate.

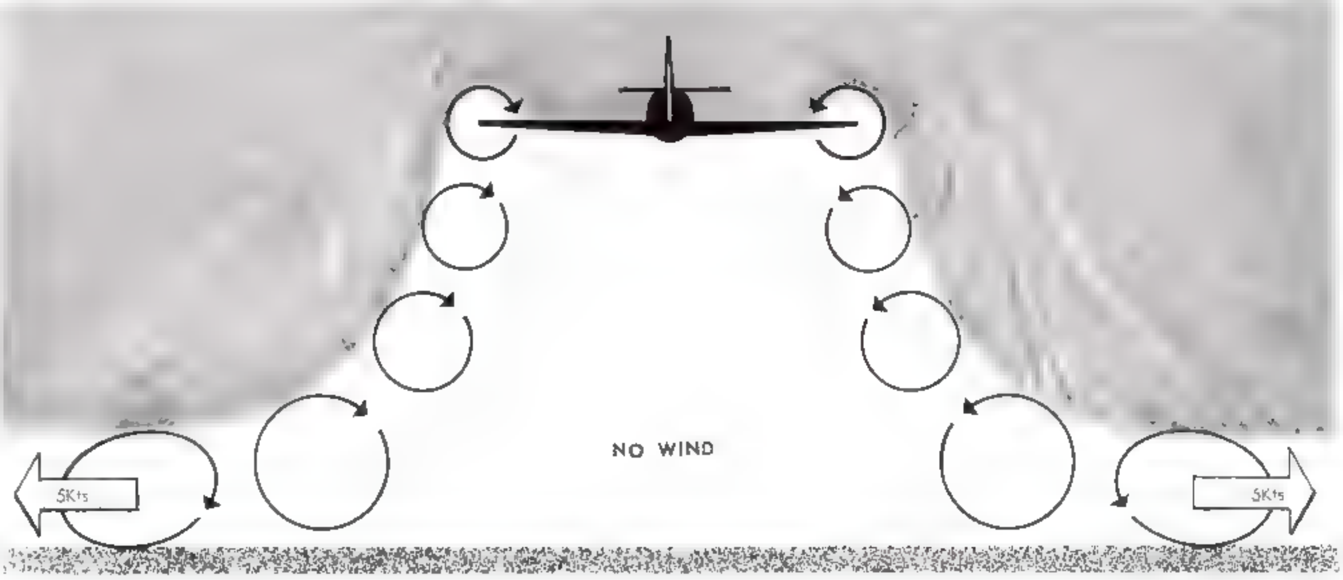


Figure 10-25. Vortex Movement In Ground Effect (No Wind).

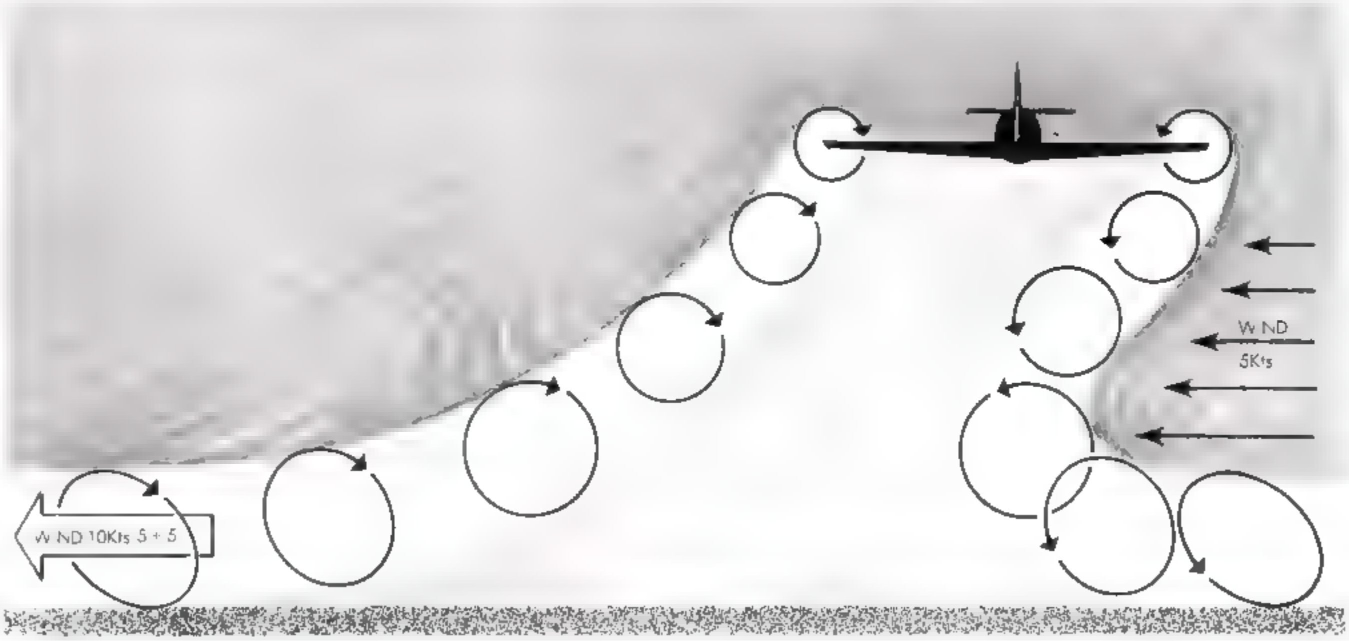


Figure 10-26. Vortex Movement In Ground Effect (Cross Wind).

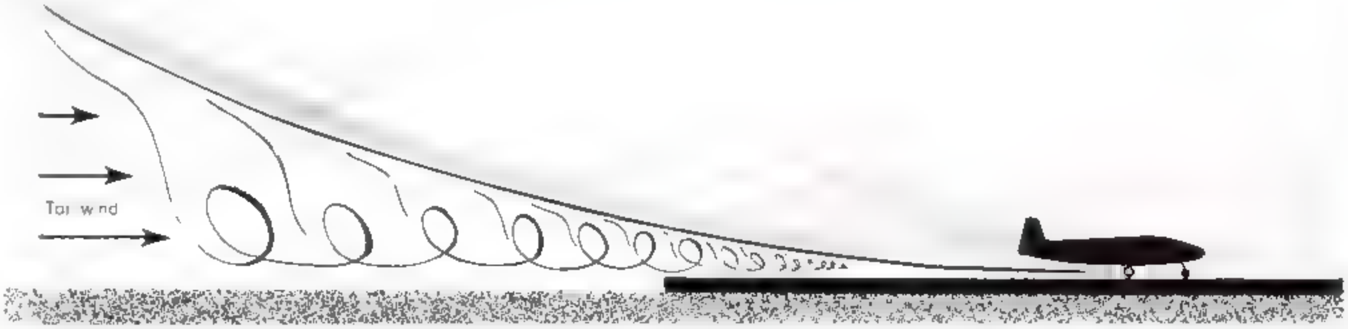


Figure 10-27. Vortex Movement Forward Of Touchdown Zone (Tail Wind).

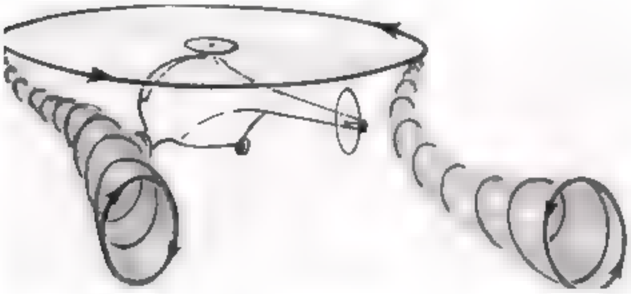


Figure 10-28. Helicopter Vortices.

Under certain conditions, airfield traffic controllers apply procedures for separating aircraft from heavy jets or large aircraft. But ultimately it is the aircrew's responsibility to anticipate and avoid areas of possible vortex wake turbulence. The following vortex avoidance procedures are recommended for the various situations.

- Enroute - fly at or above a large aircraft's flight path
- Landing behind a large aircraft - land beyond a heavy aircraft's touchdown point.
- Landing or departing behind a departing large aircraft - land or rotate prior to the heavy aircraft's rotation point.

MEDICAL AND HUMAN FACTORS OF TURBULENCE

Turbulence can cause a variety of effects on an aircraft ranging from gentle jostling to structural damage Another important aspect about turbulence is that it can produce adverse effects on the aircrew. Aviation medicine and human factor research has shown that a severe turbulent environment can cause a compromise of aircrew performance in the following ways:

- Cause a startle reaction.
- Delay decision time.
- Produce involuntary control movements which may not be obvious to the aircrew.
- Produce sensory illusion Tests have revealed that some pilot reports of extreme turbulence have actually been a visual problem. Turbulence in the range of 4 cps (cycles per second) is at a natural frequency where human visual acuity deteriorates. Reports of instruments being unreadable in turbulence at this frequency reveal through photos, that while indicating clearly, they may not be read clearly

These effects can lead to loss of control of the aircraft.

CATEGORIES OF TURBULENCE INTENSITY

Classification of turbulence intensity is difficult for both the crew member reporting turbulence and the forecaster predicting it. The crew member's judgment of turbulence severity may be influenced by the length of time the aircraft is subjected to turbulence; brief encounters likely will not be considered as significant as those lasting several minutes. Crew members' experience in turbulent conditions and in various aircraft types also affects their evaluation of the turbulence intensity.

Forecasters have no direct measurement of turbulence. They have a good knowledge of terrain features and meteorological indicators that cause turbulence, but the meteorological indicators most valuable to them are available only at infrequent intervals and at widely separated locations. Thus, forecasters are more dependent on pilot reports in forecasting turbulence than in forecasting almost any other atmospheric condition.

The aviation community, in order to provide a standard for reporting and describing turbulence, has classified turbulence into four intensities according to its effect on aircraft and occupants. Each Enroute Supplement lists these intensities and their effects. Because of the different effects of turbulence on different types of aircraft, the *type of aircraft* should always be included in reports from aircrews and, in turn, from the forecaster to other aircrews during weather briefings or when relaying reports to aircrews in flight.

CHAPTER 11

LOW LEVEL WIND SHEAR

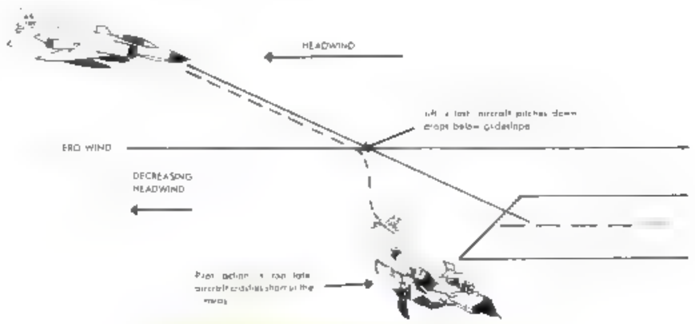
Wind shear is a change in wind speed and/or direction over a short distance, which results in a tearing or shearing action. Although wind shear can occur at any altitude, it is particularly hazardous when it happens over a short period of time within 2,000 feet of the ground during takeoff or landing. During this phase of flight, the aircraft operates only slightly above stall speed, and a major change in wind velocity can lead to a loss of lift. If the loss is great enough that the power response is inadequate, it results in a high rate of descent. The altitude at which the encounter occurs, the pilot reaction time, and the airplane response capability determine if the descent can be slowed in time to prevent an accident.

The time dependency of significant low level wind shear can be illustrated by example. Suppose an aircraft flying into a direct headwind of 30 knots flies through a gradual changing wind pattern, such that one hour later the wind has become a tailwind of 30 knots. The effect of such a gradual shear is negligible. However, if the same change occurred over a time span of a few seconds, the aircrew would have to make rapid, positive inputs to maintain control of the aircraft.

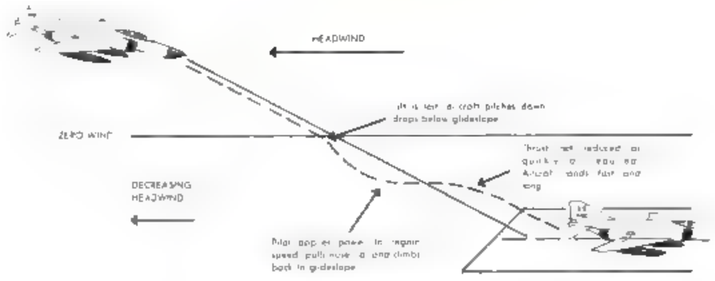
PERFORMANCE DECREASING SHEAR

When an aircraft traverses into a decreasing headwind over a short time period, the relative velocity of air over the wings decreases and the indicated airspeed decreases. Since lift is dependent upon relative velocity of air over the wings, lift decreases, the airplane tends to nose over, and an associated change in the vertical velocity indicator (VVI) readout will occur. The decreasing headwind shear condition is therefore *performance decreasing.*

The obvious hazard associated with performance-decreasing wind shear during approach and takeoff is a significant loss of lift. An aircraft operating at low speeds and low altitudes in a high drag configuration can ill afford a sudden decrease in airspeed (figure 11-1A). When the shear is encountered, the airplane reaction is a drop in airspeed and a loss of altitude. The pilot must be ready to add power when indicated airspeed starts to decrease. Once speed and glide path are regained, however, prompt reduction of thrust is necessary. It will now require less thrust and a greater rate of descent to maintain the proper profile in the decreased headwind. If the initial corrections of increased thrust and pitch are not promptly removed after regaining glide path and airspeed, a long landing at high speed may result (figure 11-1B).


HEADWIND
Lift is lost, aircraft pitches down, drops below glideslope
ERO WIND
DECREASING HEADWIND
Pilot action is too late; aircraft crashes short of the runway

A. Performance decreasing shear at an altitude too low for recovery


HEADWIND
Lift is lost, aircraft pitches down, drops below glideslope
ZERO WIND
Thrust not reduced as quickly as you should. Aircraft lands fast and long
DECREASING HEADWIND
Pilot applies power to regain speed, pulls nose up and climbs back to glideslope

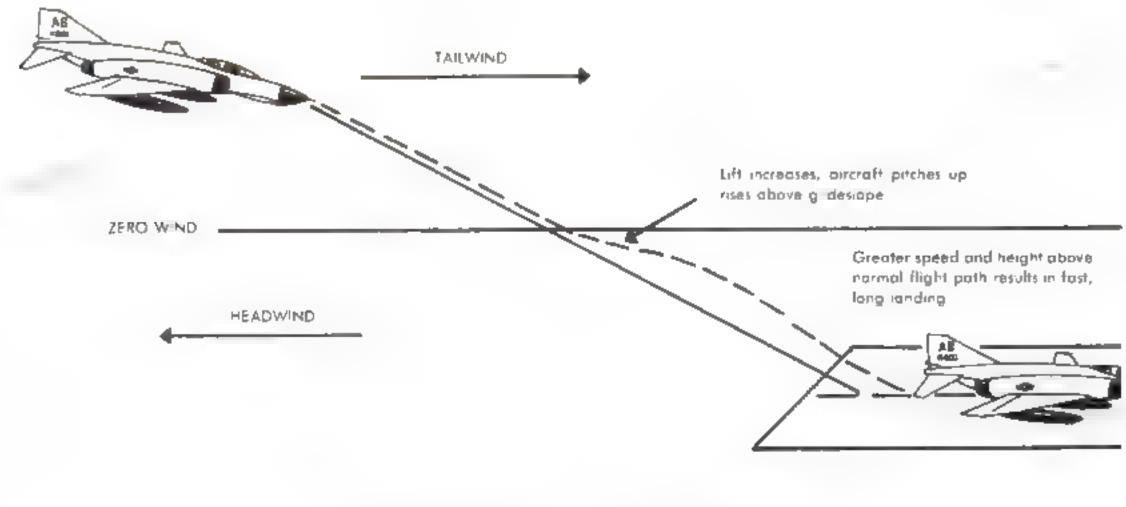
B. Performance decreasing shear where over correction results in a long landing

Figure 11-1. Performance Decreasing Shear.

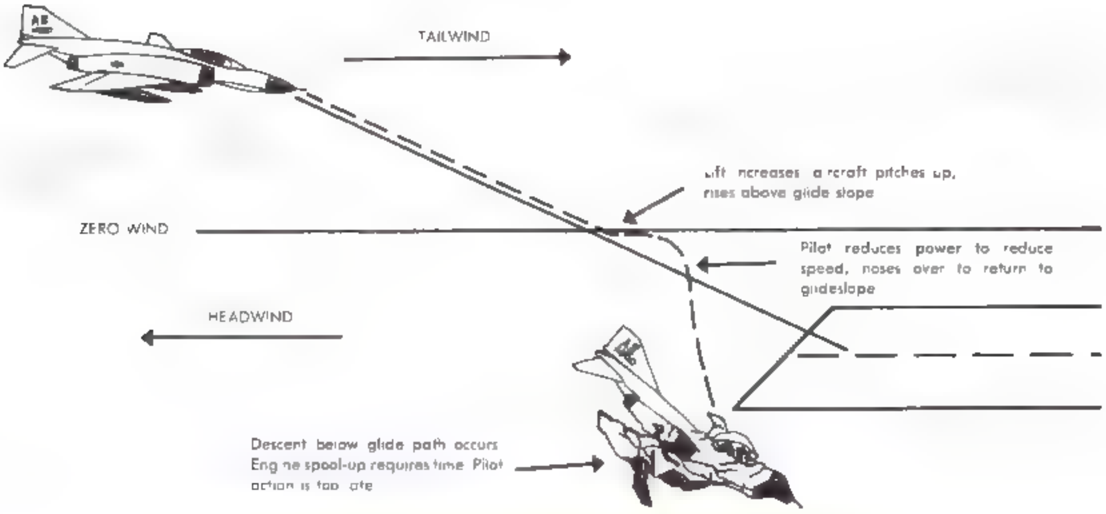
PERFORMANCE INCREASING SHEAR

When an aircraft traverses from a tailwind to a headwind over a short time span, the relative velocity of air over the wings increases and the indicated airspeed increases, lift increases, the airplane tends to nose up, and an associated change in the VVI readout will occur This wind shear condition is *performance increasing*

The obvious hazard of performance increasing wind shear is the risk of landing long (figure 11 2A) However, another hazard exists. An aircraft on approach experiences a sudden increase in airspeed and a marked decrease in downward vertical velocity. The most probable reaction of the pilot is to reduce power and nose the airplane down to reestablish position on the glidepath. The deceleration forces working on the airplane are the sum of the reduced power plus the headwind component. By the time the deceleration forces slow the airplane to such a speed that it becomes obvious to the pilot that the airplane is power deficient, it may well be too late to recover (figure 11 2B)


TAILWIND
Lift increases, aircraft pitches up
rises above glideslope
ZERO WIND
Greater speed and height above
normal flight path results in fast,
long landing
HEADWIND

A. Performance increasing shear resulting in a long landing


TAILWIND
Lift increases aircraft pitches up,
rises above glide slope
ZERO WIND
Pilot reduces power to reduce
speed, noses over to return to
glideslope
HEADWIND
Descent below glide path occurs
Engine spool-up requires time Pilot
action is too late

B. Performance increasing shear where over-correction results in impact short of runway

Figure 11-2. Performance Increasing Shear.

WEATHER CAUSING LOW LEVEL WIND SHEAR

There are several weather phenomena that produce low level wind shear. These include thunderstorms, fronts, low level jets at the top of a radiation inversion, funneling winds, and mountain waves.

Thunderstorms

The winds around a thunderstorm are complex (figure 11-3). Downdrafts exiting the base of a thunderstorm spread outward in all directions upon approaching the surface and form an area of gustiness near the thunderstorm. The outer limit of this gusty area is referred to as the *gust front.*

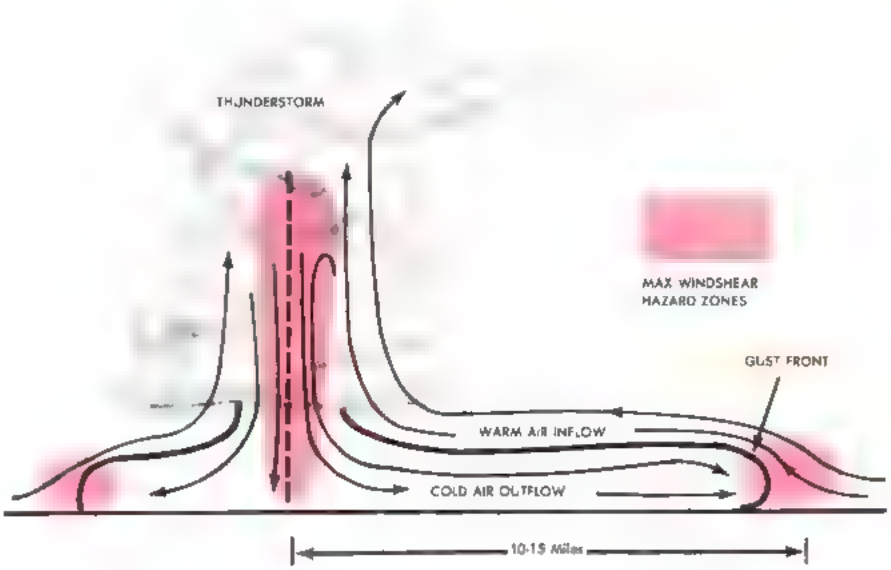


Figure 11-3. Thunderstorm Wind Shear Hazard Zones.

The gust front frequently extends 10 to 15 miles away from the thunderstorm. Extreme wind shears of 10 knots per 100 feet of altitude have been measured immediately behind the gust front, while horizontal wind shears of 40 knots per mile have been recorded across the gust front. In addition to the tremendous speed shears reached, most severe thunderstorms produce directional shears of 90° to 180°.

The thunderstorm downdraft may produce the most dangerous of shear conditions associated with the outflow of a thunderstorm. For example, in figure 11-4A an aircraft passing through the gust front and downdraft along path AB would encounter not only a rapid change in the horizontal wind field but also a downward vertical motion. The downward vertical motion can add or subtract 100 feet per minute or more to the descent or ascent rate of the aircraft and cause it to crash. In figure 11-4B the departing aircraft would experience both a downdraft and tailwind while still near the ground. The resulting loss of lift could prove disastrous to the aircrew

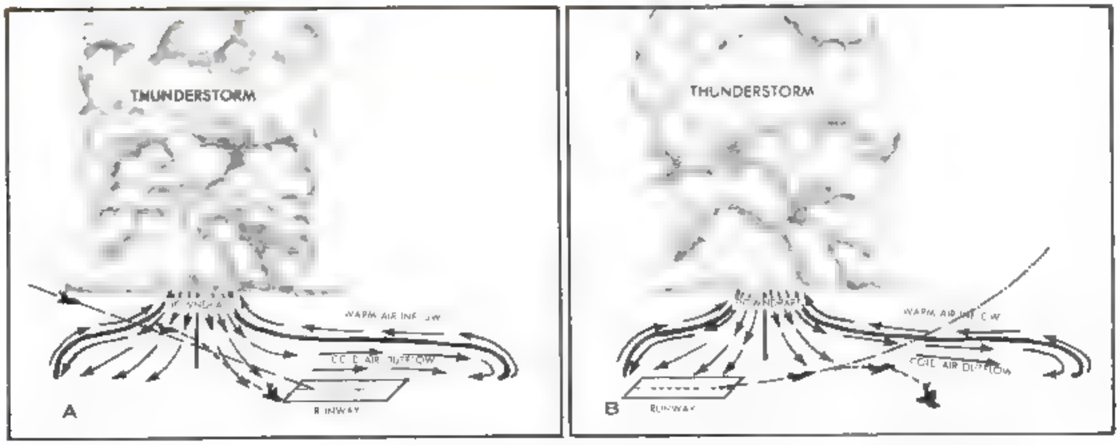


Figure 11-4. Wind Shear Associated With Thunderstorm Downdraft.

Wind shear associated with thunderstorms is by far the most hazardous due to the complexity and multiplicity of the shears produced. Prevailing low level winds are forced up over the gust front; currents that feed into the storm are present, and more than one gust front may be encountered due to multiple downdrafts. In addition, extreme downdrafts may occur beneath the central region of the storm. Simulator tests have shown that very experienced pilots have extreme difficulty flying a successful approach in thunderstorm-associated wind shear and frequently are unsuccessful. Making an approach or attempting takeoff into an environment of rapidly changing wind direction and speed can be disastrous and should be avoided if possible (figure 11-5).

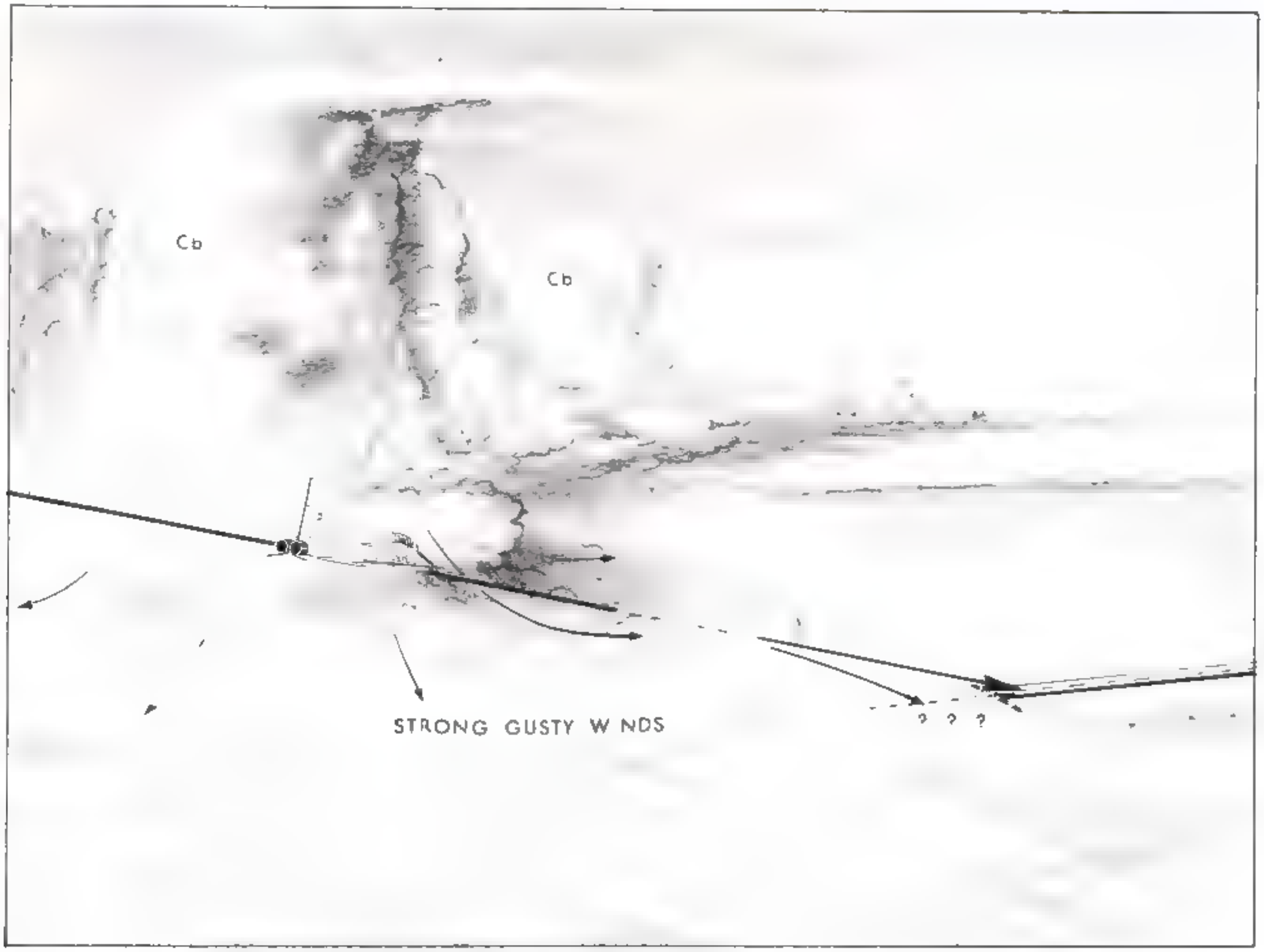


Figure 11-5. Approach and Takeoff Can Be Dangerous In Rapidly Changing Shear Conditions.

Fronts

Winds can be significantly different in the two air masses which meet to form a front. Fronts that are most conducive to significant wind shear are fast moving (30 knots or more) and/or have at least a 5°C (10°F) temperature differential

Low level wind shear occurs with a cold front after the front passes the aerodrome. Because cold fronts have a greater slope and normally move faster than warm fronts, the duration of low level wind shear at a station is usually less than two hours.

Wind shear associated with a warm front is more dangerous to aerodrome operations. Strong winds aloft, associated with the warm front, may cause a rapid change in wind direction and speed where the warm air overrides the cold, dense air near the surface (figure 11-6). Warm frontal wind shear may persist six hours or more over an airfield ahead of the front because of the front's shallow slope and slow movement. Further, low ceilings and visibilities frequently associated with warm fronts may compound aircrew problems.

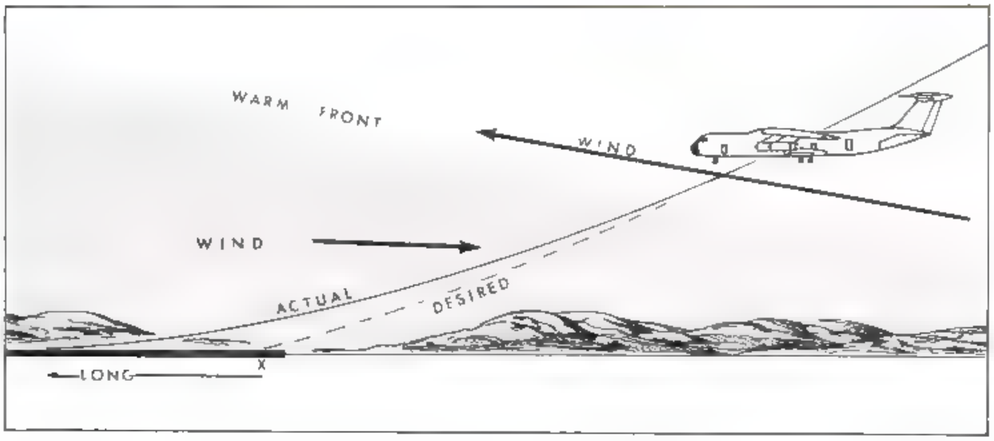


Figure 11-6. Wind Shear In A Warm Front.

Low Level Jet at Top of Radiation Inversion

The low level jet often forms just above a radiation inversion. It starts to form at sundown, reaches maximum intensity just before sunrise, and is destroyed by daytime heating (usually by 10 A.M. local time). The low level jet is observed in all parts of the world at all times of the year. In the United States it is common in the Great Plains and central states.

The cooling of the earth creates a calm, stable dome of cold air 300-1,000 feet thick, termed an inversion layer (see Chapter 3). The low level jet occurs just above the top of the inversion layer, and while speeds of 30 knots are common, windspeeds in excess of 65 knots have been reported. Anytime a radiational inversion is present, the possibility of low level wind shear exists (figure 11-7).

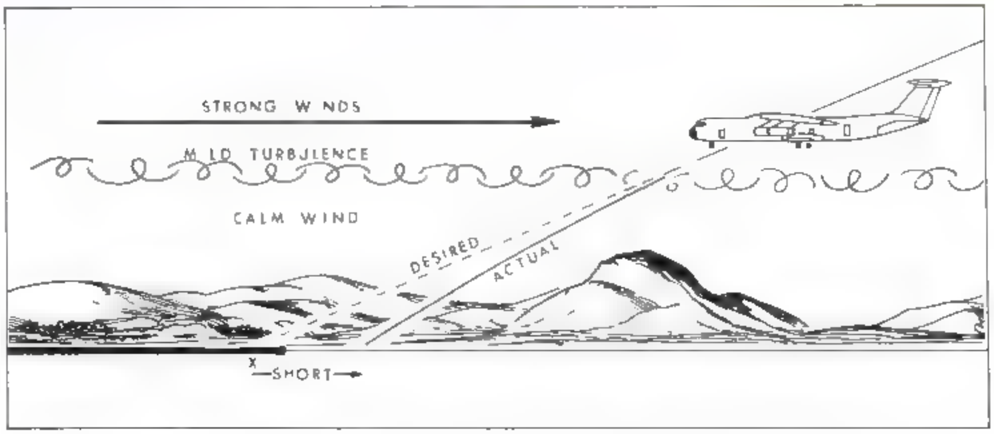


Figure 11-7. Wind Shear During Radiation Inversion.

Funneling Winds and Mountain Waves

Certain aerodromes are infamous for the treacherous winds that frequently exist. These winds are caused by funneling, i.e., the terrain is such that the prevailing winds force a large mass of air to be channeled through a narrow space (such as a canyon) where it is accelerated and then spills out into the flightpath of aircraft. These winds sometimes reach velocities of 80 knots. Caution is required when conducting operations near mountains or along straits and channels (figure 11 8).

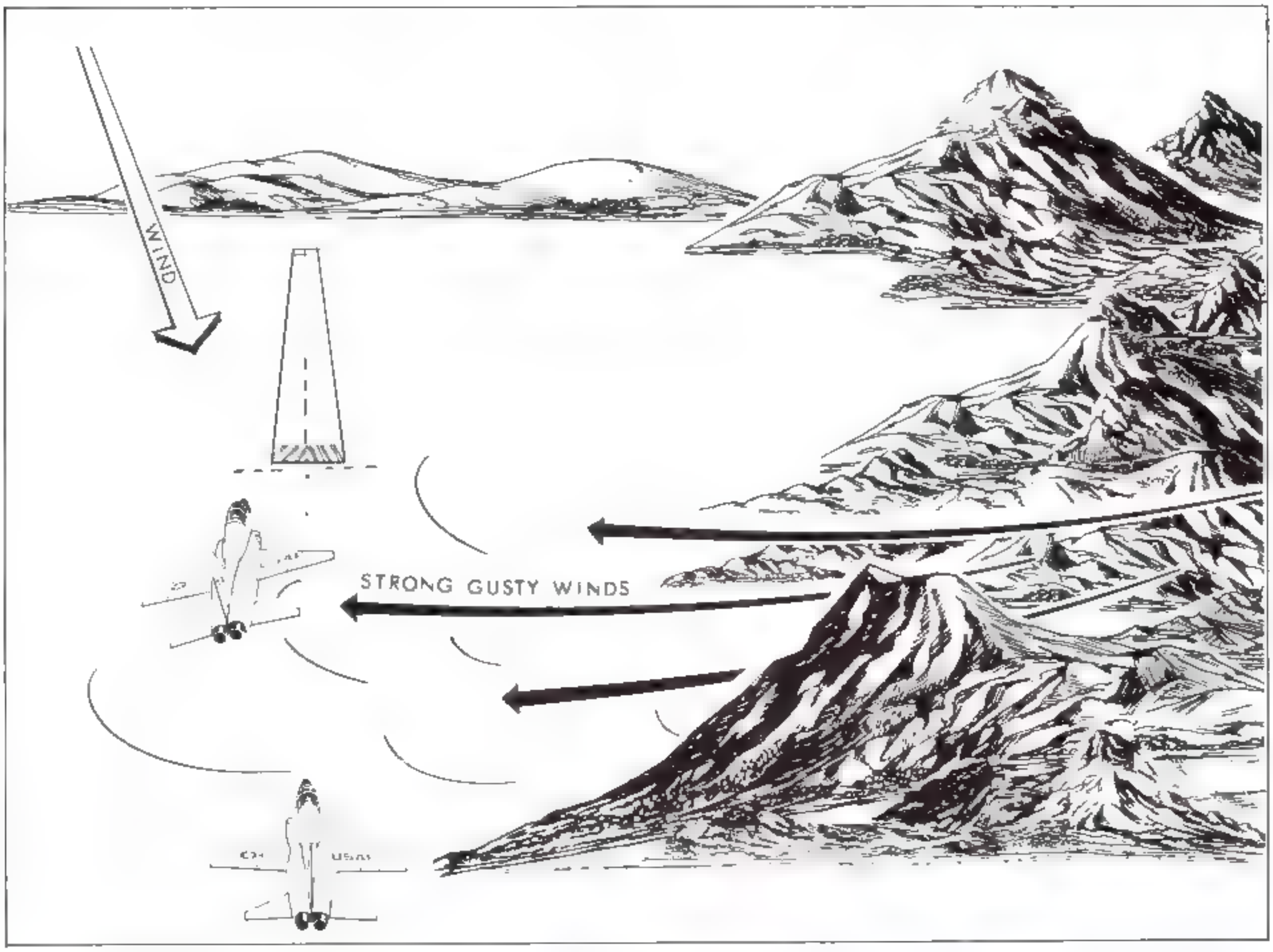


Figure 11-8. A Wind Funneling Condition.

Mountain waves (see Chapter 10) often create low level wind shear at aerodromes that lie downwind of the wave. While not a prerequisite, altocumulus standing lenticular (ACSL) clouds usually indicate the presence of mountain waves, and they are clues that shear should be anticipated.

Other Causes of Low Level Wind Shear

Two less prominent sources of low level wind shear deserve brief discussion: gusty or strong surface winds and land/sea breezes. Fluctuations of 10 knots or more from the mean sustained wind speed or strong winds blowing past buildings and structures near a runway can produce localized areas of shear. This type of shear can be particularly hazardous to light aircraft. Observing the local terrain and requesting pilot reports of conditions near the runway are the best means for anticipating wind shear from this source

Land and sea breezes commonly occur near large lakes, bays, or oceans (see Chapter 5). The flow to or from the water is caused by differential heating and cooling of land and sea surfaces. The sea breeze is a small scale frontal boundary and can reach speeds of 15 to 20 knots It can move inland 10 to 20 miles, reaching its maximum penetration in mid or late afternoon. The depth of the breeze is approximately 2,000 feet. Land breezes occur at night because the land becomes cooler than the water. The land breeze has less intensity than the sea breeze, and unless aircraft penetrate it on a long, low approach over water, there is little threat to flying safety

INDICATIONS OF WIND SHEAR

Although the conditions that produce wind shear can be forecast, it is frequently impossible to forecast the exact location and magnitude of the shear (as in the complex case of thunderstorms). However, there are ways crew members can alert themselves to the possibility of a wind shear condition and detect it when encountered

A recent cold frontal passage or an impending warm frontal passage is an indicator of possible wind shear. The isobars around the frontal system at the surface yield a good approximation of the directional shear that will be encountered. For example, in figure 11-9, the surface winds at airport A are reported to be 320° at 25 knots and at airport B 040° at 20 knots The direction of the isobars in the warm sector (from about 220°) is an approximation of the wind direction above both the cold and warm frontal surfaces. Therefore, a pilot flying an approach to or making a departure from either airport A or B can expect winds to be from a direction of about 220° above the frontal surfaces, shearing to about the same direction of the reported surface wind below the frontal surfaces.

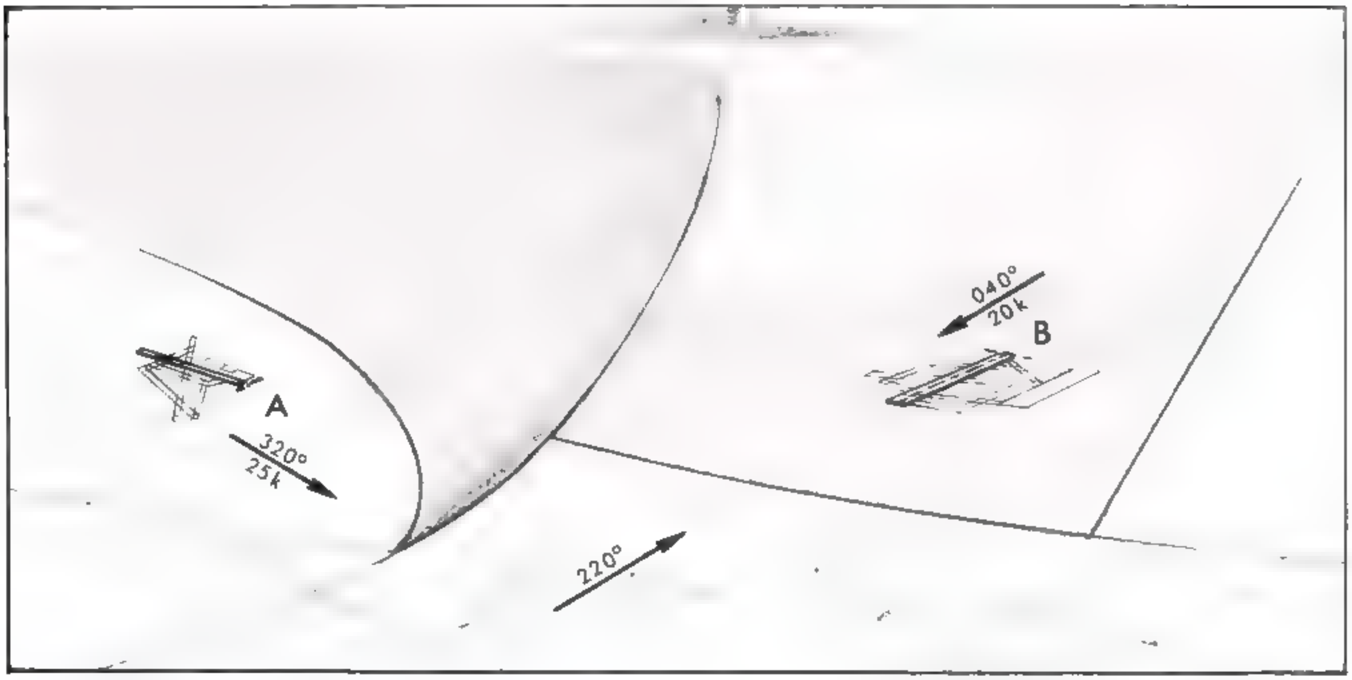


Figure 11-9. Isobars Approximate Directional Shear.

Another indicator to the aircrews is an abnormal power setting and rate of descent required for the approach. The rate of descent required to maintain a given glide slope is based on groundspeed. Therefore, a tailwind during approach requires a reduced power setting and an increased rate of descent in order to maintain the glidepath. Conversely, a headwind during approach requires an increased power setting and a decreased rate of descent in order to maintain the glidepath.

The best indication to the aircrew that the aircraft is encountering wind shear occurs on the instrument panel. Fluctuations in the indicated airspeed and the vertical velocity indicator always accompany wind shear. Another indication is a large difference between indicated airspeed and groundspeed. Any rapid changes in the relationship between the two represent a wind shear.

Crews in aircraft equipped with an inertial navigation system (INS) can compare the wind at the initial approach altitude with the reported runway surface wind to see if there is a wind shear situation between the aircraft and the runway. Remember: INS winds are in degrees true; tower winds are in degrees magnetic. This will make little difference at airfields where variation is only a few degrees, but it makes a considerable difference when variation is 20 degrees or greater.

HOW TO FLY WIND SHEAR

The most important elements for the aircrew in coping with a wind shear environment are the crew's awareness of an impending wind shear encounter and the crew's decision to avoid the encounter or to *immediately* respond if an encounter occurs.

During takeoff, if a tailwind shear or gust front from a thunderstorm is anticipated, it is important to penetrate the shear at a relatively high airspeed. A departure route that will provide the most favorable wind condition (generally a headwind) should be used. If necessary, delay the takeoff until the shear situation subsides.

Aircrews must be alert to the possibility of wind shear on all approaches. During an approach, the comparison of actual groundspeed and a *reference groundspeed* is a proven procedure for detecting and coping with low level wind shear. Reference groundspeed is computed by subtracting the surface headwind component or adding the tailwind component to approach true airspeed.

If actual groundspeed exceeds reference groundspeed, a decreasing tailwind condition will occur. If actual groundspeed is less than reference groundspeed, a decreasing headwind condition will occur

If a decreasing tailwind condition is experienced, maintain computed approach speed. If a decreasing headwind condition is experienced, maintain the reference groundspeed to provide the necessary energy to penetrate the shear safely or go around

If wind shear is encountered on final approach, do not hesitate to go around if the approach profile and airspeed cannot be reestablished. A go-around is often the aircrew's best course of action. If necessary, delay the approach until the shear situation has subsided or divert to a suitable alternate. Finally, when wind shear is encountered, pass this information, including magnitude of airspeed change and altitude of occurrence, to air traffic control and the base weather station so that other aircrews may be informed.

CHAPTER 12

AIRCRAFT ICING

Aircraft icing is one of the major weather hazards to aviation. Its formation on either fixed or rotary wing aircraft can disrupt the smooth flow of air over the airfoils and therefore decrease lift and increase weight, drag, and stalling speed. In addition, the accumulation of ice on exterior movable surfaces affects the control of the aircraft. If ice begins to form on the blades of the propeller, the propeller's efficiency is decreased and still further power is required to maintain flight. Another significant hazard is that ice accumulation on rotors and propellers can result in a disastrous vibration. Further, ice can form in the air intake of an engine, robbing the engine of air to support combustion, or ice may be ingested into the engine, causing foreign object damage (FOD). Other icing effects include loss of proper operation of control surfaces, brakes, and landing gear, reduction or loss of aircrew's outside vision, false flight instrument indications, and loss of radio communication

Aircraft icing can be classified into two main groups: structural and induction. These icing groups will be discussed in detail, including the conditions which contribute to ice formation, the types of icing, intensities of icing, and where icing is most likely to be found.

STRUCTURAL ICING

Two conditions must be met for structural ice to form on an aircraft. First, the free-air temperature and the aircraft surface temperature must be at or below freezing. Second, supercooled visible water droplets (liquid water droplets at subfreezing temperatures) must be present or a high humidity must exist.

Free-Air Temperature

Wind tunnel experiments reveal that when saturated air flows over a stationary object, ice may form on the object when the air temperature is as high as 4°C. The temperature of the object is cooled by evaporation and pressure changes in the moving air currents. Conversely, the object is heated by friction and by the impact of water droplets. When an aircraft travels at less than about 400 knots true airspeed, the cooling and heating effects tend to balance. Therefore, structural ice may form when the free-air temperature is 0°C or colder. Ice is seldom encountered at temperatures below -40°C.

Supercooled Visible Liquid Water and High Humidity

Clouds are the most common forms of visible liquid water. Water droplets in the free air, unlike bulk water, do not freeze at 0°C. Instead, their freezing temperature varies from -10°C to -40°C. The smaller the droplets, the lower the freezing point. As a general rule, serious icing is rare in clouds with temperatures below -20°C since these clouds are almost completely composed of ice crystals. However, crew members must recognize that icing is possible in any cloud where the temperature is at or below 0°C. In addition, frost sometimes forms on an aircraft in clear humid air if both aircraft and air are at subfreezing temperatures.

Freezing rain and drizzle, which may be encountered in the clear air below a cloud deck, are other forms of visible liquid moisture that causes icing. Freezing precipitation is probably the most dangerous of all icing conditions. It can build hazardous amounts of ice in a few minutes and is extremely difficult to remove.

TYPES OF STRUCTURAL ICING

Aircraft structural icing consists of three basic types: clear, rime, and frost. Also, mixtures of clear and rime are common. The type of icing that will form depends primarily upon the water-droplet size and temperature.

Clear Ice

Clear ice is a glossy ice identical to the glaze which forms on trees and other objects as freezing rain strikes the earth. Clear ice is the most serious of the various forms of ice because it adheres so firmly to the aircraft. Conditions most favorable for clear ice formation are high water content, large droplet size, and temperature slightly below freezing. Clear ice normally forms when the temperatures are between 0° and -10°C, but can be encountered in cumulonimbus clouds to temperatures as cold as -25°C. It is most frequently encountered in cumuliform clouds and freezing precipitation.

Clear ice can be smooth or rough. It is smooth when deposited from large, supercooled cloud droplets or raindrops that spread and take the shape of the aircraft surface and freeze slowly. If mixed with snow, ice pellets or small hail, it is rough, irregular, and whitish (figure 12-1). The deposit then becomes very blunt-nosed with rough bulges building out against the airflow.

Clear ice may also be a problem on the ground when the aircraft is exposed to freezing precipitation. Another ground hazard may occur when ice forms, during takeoff or landing, as a result of splashing water or mud which may be on the taxi strip or runway. In either case, control surfaces could be prevented from operating properly.

Rime Ice

Rime ice is a milky, opaque, and granular deposit of ice with a rough surface (figure 12-2). It is formed by the instantaneous freezing of small, supercooled water droplets as they strike the aircraft. This instantaneous freezing traps a large amount of air, giving the ice its opaqueness and making it very brittle. It is most likely to accumulate when the temperatures are between 0° and -20°C but can be expected in thunderstorms as cold as -40°C. Rime ice is most frequently encountered in stratiform clouds but may also occur in cumulus-type clouds. It is comparatively easy to remove by conventional methods, even though it distorts the airfoil more than clear ice.

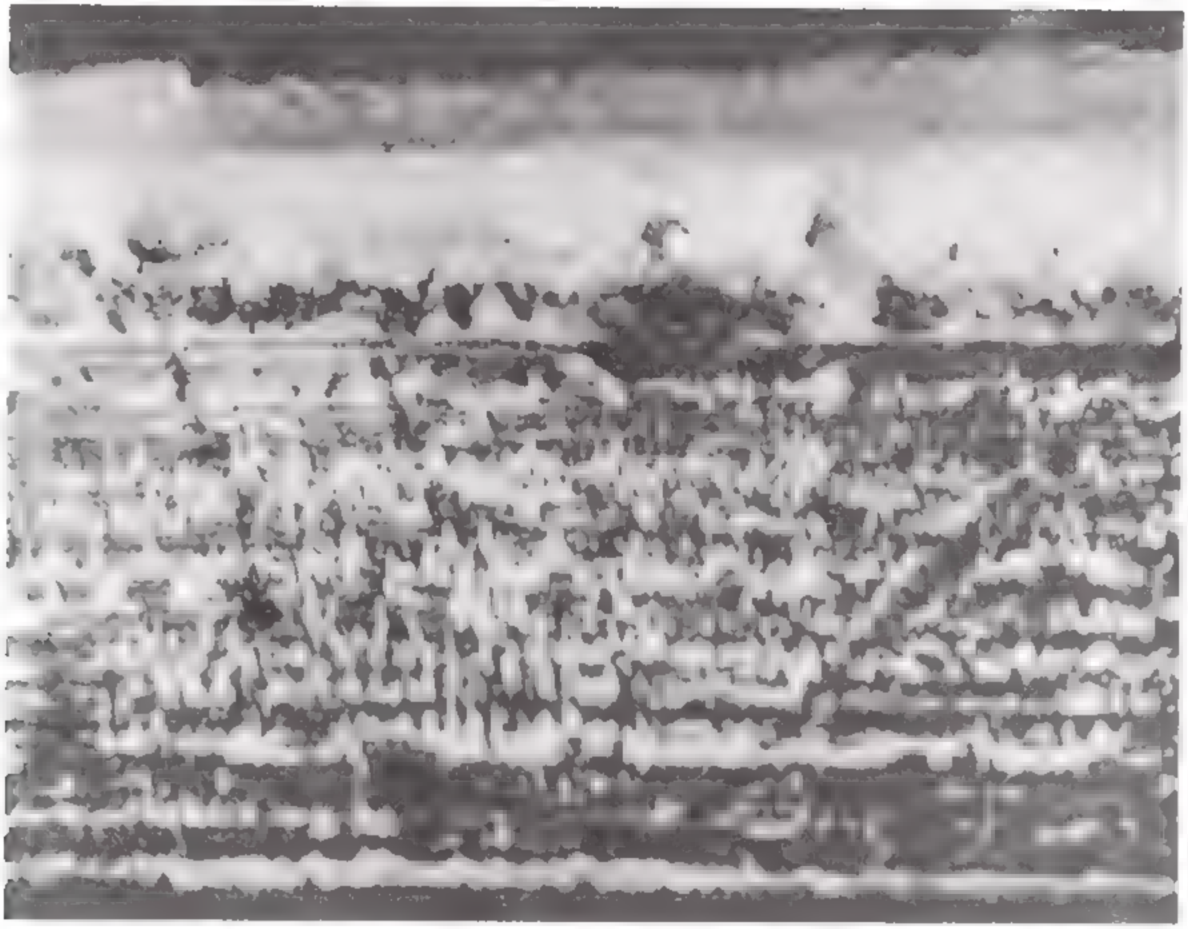


Figure 12-1. Clear Ice Can Be Smooth Or Rough.

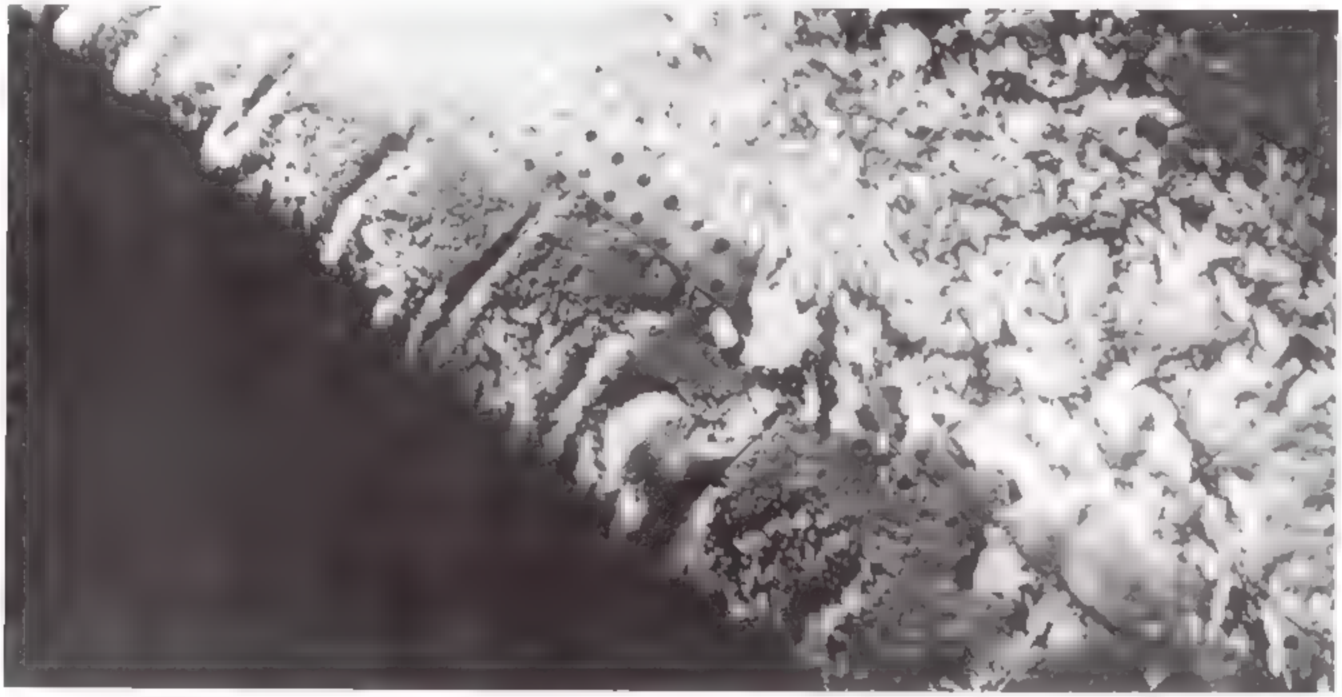


Figure 12-2. Rime Ice Is Milky, Opaque, and Granular.

Frost

Frost is a deposit of a thin layer of crystalline ice (figure 12-3). It forms on the exposed surfaces of parked aircraft when the temperature of the exposed surface is below freezing (while the free-air temperature may be above freezing). The deposit of ice forms during night radiational cooling in a manner similar to the formation of frost found on the ground.

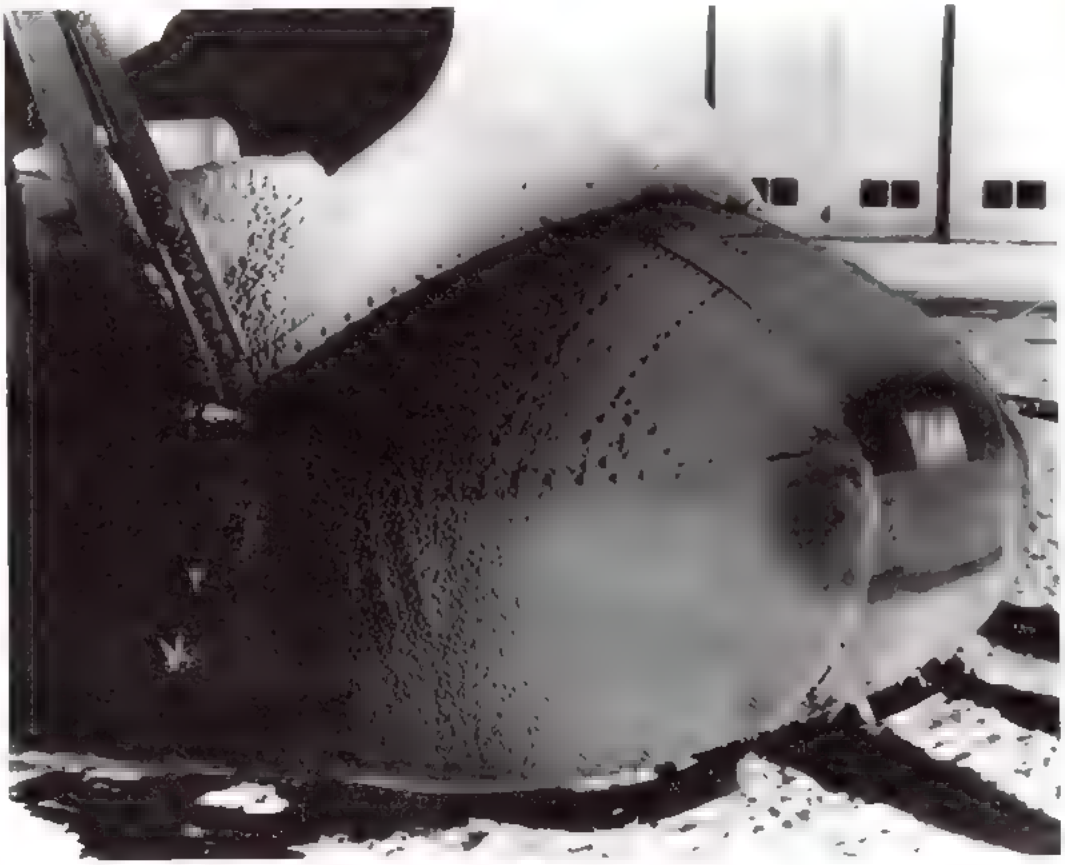


Figure 12-3. Frost On The Exposed Surfaces Of Parked Aircraft.

Frost may also form on aircraft in flight when a cold aircraft descends from a zone of subzero temperatures to a warmer, moist layer below. The air is chilled suddenly to below-freezing temperature by contact with the cold aircraft, and sublimation (formation of ice crystals directly from water vapor) occurs Frost can cover the windshield or canopy and completely restrict outside vision.

Frost is a most deceptive form of icing. It affects the lift drag ratio of an aircraft and is a definite hazard during takeoff. All frost should be removed from the aircraft prior to takeoff.

INTENSITIES OF STRUCTURAL ICING

The amount of ice that an aircraft will accumulate in a given case depends considerably on the characteristics of that particular aircraft. Therefore, general intensity classifications for reporting icing are given in the weather section of the FLIP Enroute IFR Supplement.

ICE FORMATION ON FIXED WING AIRCRAFT

The relatively thick wings, canopies, and other features of conventional aircraft have a smaller collection potential than those of the trimmer and faster turbojet aircraft. However, the actual hazard of icing for conventional aircraft tends to be greater than for jets because of less aerodynamic heating at lower airspeed. Conventional aircraft are subjected to icing conditions over longer periods and operate at altitudes more conducive to icing.

Wing and Tail Surfaces

Ice accumulations on wing and tail surfaces disrupt the flow of air around these airfoils (figure 12-4). This results in a loss of lift, an increase in drag, and causes the aircraft to stall at a higher airspeed than normal (figure 12-5). The weight of the ice deposit presents less danger, but it also may become important when too much lift and thrust are lost.

Experiments have shown that ice deposits of only one-half inch on the leading edge of airfoils on some aircraft reduce their lifting power as much as 50 percent and increase the drag on the aircraft by an equal amount, thereby greatly increasing the stalling speed. The serious consequences of these effects are obvious. It should be remembered that one-half inch or more of ice can accumulate in a minute or two in some cases.

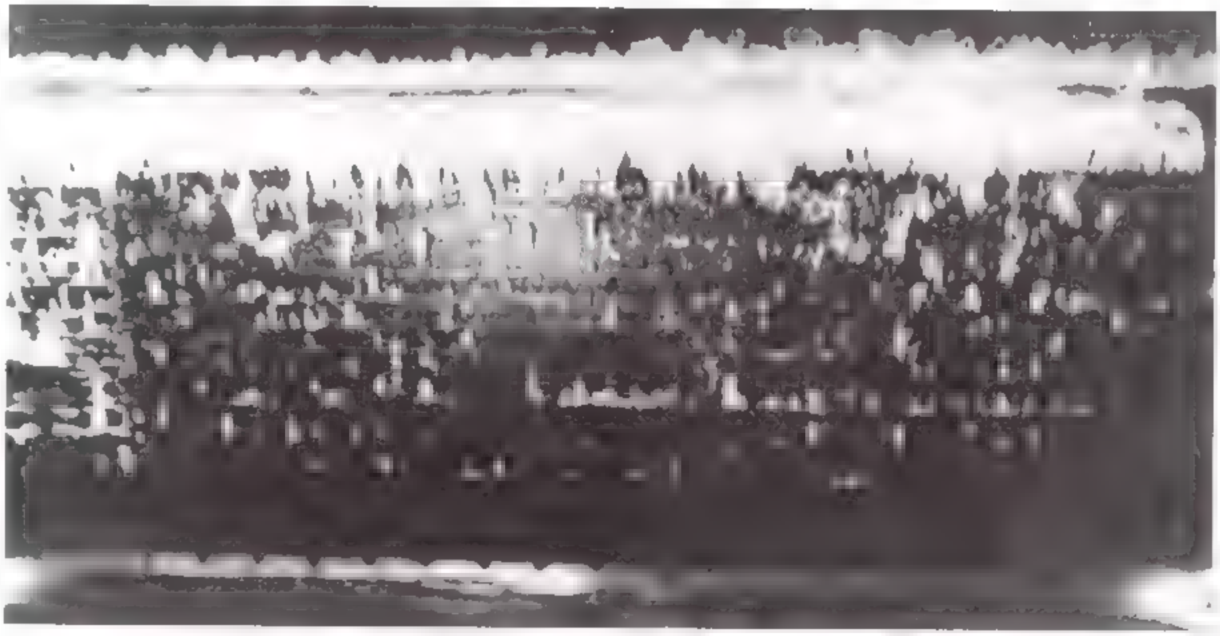


Figure 12-4. Ice Accumulation Disrupts Air Flow.

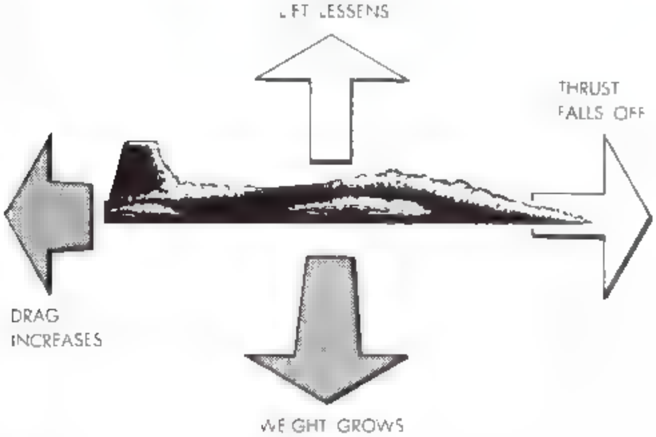


Figure 12-5. Effects Of Icing Are Cumulative, Causing Stalling Speed To Increase.

Propellers

The accumulation of ice on the propeller hub and blades (figure 12-6) reduces the efficiency of the propeller, which in turn reduces airspeed. Increased power settings may then fail to produce sufficient thrust to maintain flying speed and more fuel is consumed

An even greater hazard is the vibration of the propeller, caused by the uneven distribution of ice on the blades. The propeller is very delicately balanced, and even a small amount of icing can create an imbalance. The resulting vibration places dangerous stress on the engine mounts as well as the propeller itself. Propellers with low revolutions-per-minute (RPM) are more susceptible to icing than propellers with high RPM. Ice usually forms faster on the hub of the propeller than it forms on the blade because the differential velocity of the blade causes a temperature increase from the hub to the propeller tip

Pitot Tube and Static Pressure Ports

Icing of the pitot tube (figure 12-7) and other static pressure ports is dangerous because it causes inaccurate indications on the altimeter, airspeed, and vertical velocity instruments. When icing is observed on any part of the aircraft, the crew should assume that the static ports are accumulating ice as fast or faster than other areas of the aircraft

Radio Antenna

The principal danger of an ice accumulation on the aircraft's radio antenna is the probable loss of radio communication. This is also a danger signal because the antenna is not likely to ice up unless other parts of the aircraft are also accumulating ice. The crew, therefore, loses their ability to request a change of altitude or course to get out of the icing zone.

Windshield

The formation of ice or frost on aircraft windshields is most hazardous during takeoffs and landings. Small frost particles on the windshield prior to takeoff may act as sublimation nuclei during takeoff and reduce visibility to near zero. Ice on the windshield during letdown may prevent visual contact with the runway.

Engines

Reciprocating engines experience icing on airscoops, scoop inlets (ducts), carburetor inlet screens, and other protuberances of the induction system. All surfaces of the engine which are exposed to water droplets may also collect ice

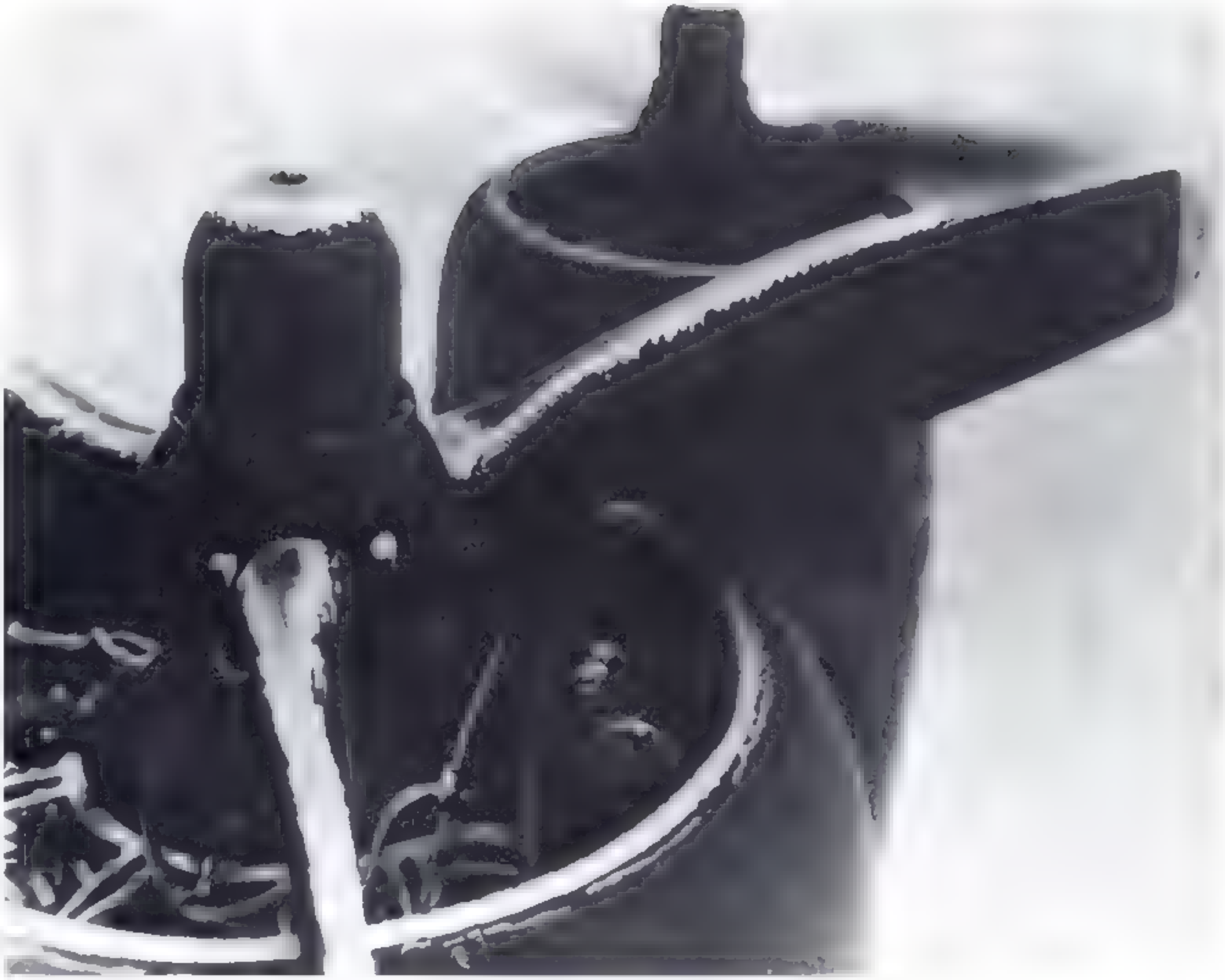


Figure 12-6. Propeller Icing.

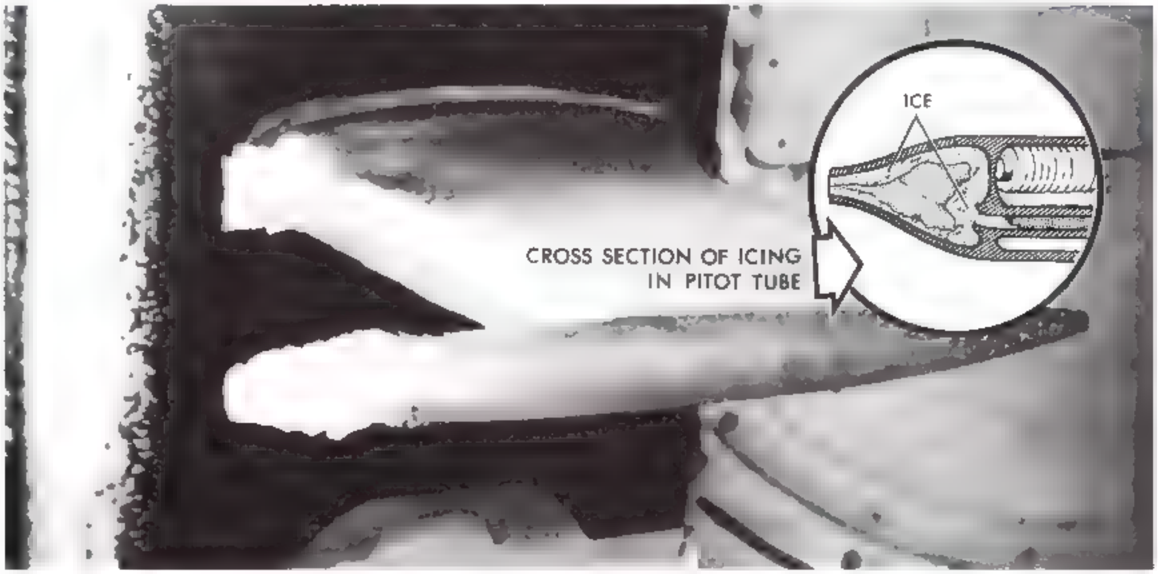


Figure 12-7. Pitot Tube Icing.

ICE FORMATION ON ROTARY WING AIRCRAFT

The problems of icing on rotary wing aircraft are related to those involving wings and propellers. Rotor icing is slightly different from propeller icing because of the lower rotational speed of the rotors. Ice accumulation on rotor blades also differs from that on fixed wings of conventional aircraft due to the smaller scale of the helicopter wing, the variation of airspeed with rotor blade span, the cyclic pitch changing of the blades, and the cyclic variation of airspeed at any given point on the blade in conditions of forward flight.

Rotor Systems

Ice formation on the helicopter main rotor system or antitorque rotor system may produce critical vibration, loss of efficiency or control, and can deteriorate significantly the available revolutions-per-minute (rpm) to a level where safe landing cannot be assured. Although the slow forward speed of the helicopter reduces ice build-up on the fuselage, the rotational speed of main and tail rotor blades produces a rapid growth rate on certain surface areas:

Main Rotor Head Assembly. Ice accumulation on the swashplates, push-pull rods, bell cranks, hinges, scissors assemblies, and other mechanisms of the main rotor head assembly interferes with collective pitch and cyclic control (figure 12-8).

Main Rotor Blades. Several factors tend to reduce ice accretion on the main rotor blades, such as the centrifugal force of rotation, the bending and flapping of the blades during rotation, the slow rotational speed of the blades near the rotor head, and the fast rotational speed near the blade tips. However, at a hover, a 3/16-inch coating of ice is sufficient to prevent some helicopters from maintaining flight. A critical icing hazard can, therefore, form rapidly on the center two-thirds of the main rotor blades (figure 12-9). The uneven accretion or shedding of this ice formation may also produce severe rotor vibration.

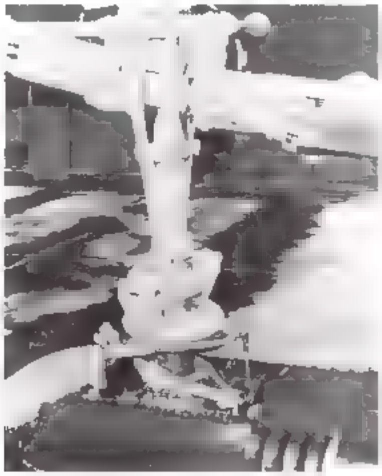


Figure 12-8. Main Rotor Head Icing.

Figure 12-9. Main Rotor Blade Icing.

Tail Rotor. Ice accumulation on either the antitorque rotor head assembly or blades produces the same hazards as those associated with the main rotor. The centrifugal force of rotation and the blade angle of incidence relative to the clouds help to reduce ice build-up on the tail rotor blades, but the shedding of ice from the blades may result in structural or foreign object damage (FOD) to the fuselage rotors or engines, and injury to ground personnel. This particular hazard appears to be more threatening to large, tandem rotor system aircraft.

Air Intake Screens

Ice accumulation on the engine and transmission air intake screens (figure 12-10) is more rapid than on the rotor systems. This results in inadequate cooling of the engine and transmission. On some helicopters, a loss of manifold pressure concurrently with air intake screen icing may force the immediate landing of the aircraft. Freezing water passing through the screens also coats control cables and may produce limited throttle movement and similar control problems.

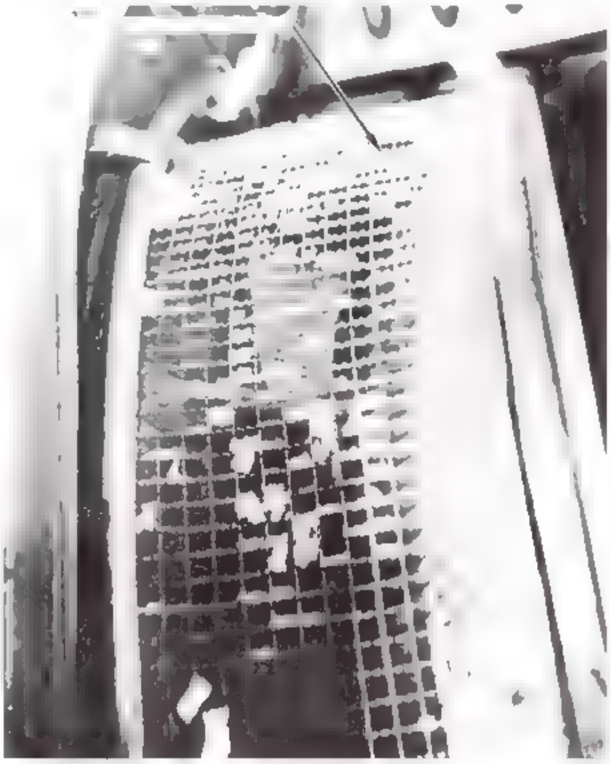


Figure 12-10. Engine Air Intake Screen Icing.

INDUCTION ICING

In addition to the hazards created by structural icing, an aircraft frequently is subjected to icing of the power plant itself The affected components supply the engine with the proper fuel and air mixture for efficient combustion Ice formation is most common in the air induction system but also may be found in the fuel system. Icing in the carburetor of piston engines is actually a combination of the two.

Carburetor Icing

Carburetor icing is treacherous. It frequently causes complete engine failure. It may form under conditions in which structural ice could not possibly form. If the relative humidity of the outside air being drawn into the carburetor is high, ice can form inside the carburetor in cloudless skies when the temperature is as high as 22°C (72°F). It sometimes forms with outside air temperatures as low as -10°C (14°F).

Carburetor ice forms during vaporization of fuel, combined with the expansion of air as it passes through the carburetor. Temperature drop in the carburetor can be as much as 40°C but is usually 20°C or less.

Ice will form in the carburetor passages (figure 12-11) if cooling is sufficient to bring the temperature inside the carburetor down to 0°C or colder and if moisture is available. Ice may form at the discharge nozzle, in the venturi, on or around the butterfly valve, or in the passages from the carburetor to the engine.

The carburetor heater is an anti-icing device which preheats the air before it reaches the carburetor, melting any ice or snow entering the intake, and keeping the mixture above the freezing point. The heater is usually adequate to prevent icing, but it will not always clear out ice which has already formed. Since carburetor heating can adversely affect aircraft performance, use it only as outlined in your aircraft flight manual.

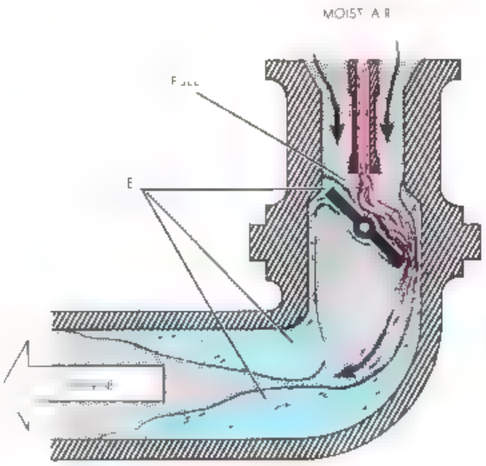


Figure 12-11. Carburetor Icing.

Power Plant Icing in Jet Aircraft

Fuel System. Since water easily mixes with jet fuel, the fuel absorbs considerable water when the air humidity is high. Occasionally, enough water is absorbed to create icing of the fuel system when fuel temperature is at or below the freezing temperature of water.

Induction System. Ice forms in the induction system any time atmospheric conditions are favorable for formation of structural icing (visible liquid moisture and freezing temperatures). In addition, induction icing can form in clear air when the relative humidity is high and the free-air temperatures generally are 10°C or colder.

Air Intake Ducts

In flights through clouds which contain supercooled water droplets, air intake duct icing is similar to wing icing. However, the ducts may ice when skies are clear and temperatures are above freezing. While taxiing, and during takeoff and climb, reduced pressures exist in the intake system (figure 12-12). This lowers temperatures to the point that condensation and or sublimation takes place, resulting in ice formation which decreases the radius of the duct opening and limits the air intake.

The temperature change varies considerably with different types of engines. Therefore, if the free-air temperature is 10°C or less (especially near the freezing point) and the relative humidity is high, the possibility of induction icing definitely exists.

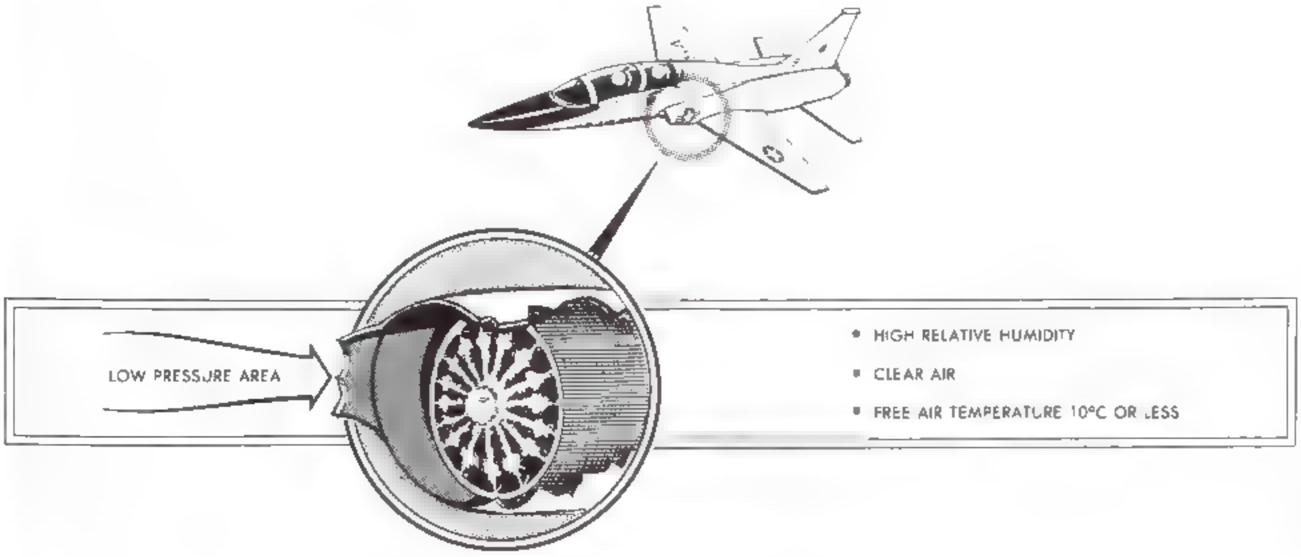


Figure 12-12. Jet Engine Induction Icing.

Inlet Guide Vanes

Icing occurs when the supercooled water droplets in the atmosphere strike the guide vanes and freeze. As ice build up increases, the reduction of air flow to the engine results in a decrease in engine thrust and eventual failure of the engine. Also, the shedding of large pieces of ice ahead of the compressor inlet may be ingested into the engine, causing severe damage

WEATHER CONDUCIVE TO AIRCRAFT ICING

Potential icing zones in the atmosphere are mainly a function of temperature and cloud structure. These factors, in turn, vary with altitude, location, weather pattern, season, and terrain

Temperature

Aircraft icing is generally limited to the layer of the atmosphere lying between 0°C and -40°C. However, icing has been reported at temperatures colder than -40°C in the upper parts of cumulonimbus and other clouds. The types of icing associated with temperature ranges are: clear, 0°C to -10°C; a mixture of clear and rime, -10°C to 15°C; rime, -15°C to -20°C and colder.

Clouds

Stratiform. Icing in middle and low level stratiform clouds is confined, on the average, to a layer between 3,000 and 4,000 feet thick. The intensity of the icing generally ranges from a trace to light, with the maximum values occurring in the upper portions of the cloud. Both rime and mixed may be found in stratiform clouds. The main hazard lies in the great horizontal extent of some of these cloud decks. High-level stratiform clouds are composed mostly of ice crystals and give little icing.

Cumuliform. The zone of probable icing in cumuliform clouds is smaller horizontally but greater vertically than in stratiform clouds. Icing is more variable in cumuliform clouds because many of the factors conducive to icing depend on the stage of development of the particular cloud Icing intensities may range from a trace in a small cumulus to moderate or severe in a large towering cumulus or cumulonimbus cloud. Although icing occurs at all levels above the freezing level in a building cumulus, it is most intense in the upper half of the cloud. Icing in a cumuliform cloud is usually clear or mixed with rime in the upper levels

Cirriform. Aircraft icing rarely occurs in cirrus clouds although some do contain a small portion of water droplets. However, icing of light intensity has been reported in the dense, cirrus anvil-tops of cumulonimbus where updrafts may maintain considerable water at rather low temperatures.

Frontal Zones

About 85 percent of all icing conditions reported occur in the vicinity of frontal zones. This icing may be in relatively warm air above the frontal surface or in the cold air beneath (figures 12-13 and 12-14).

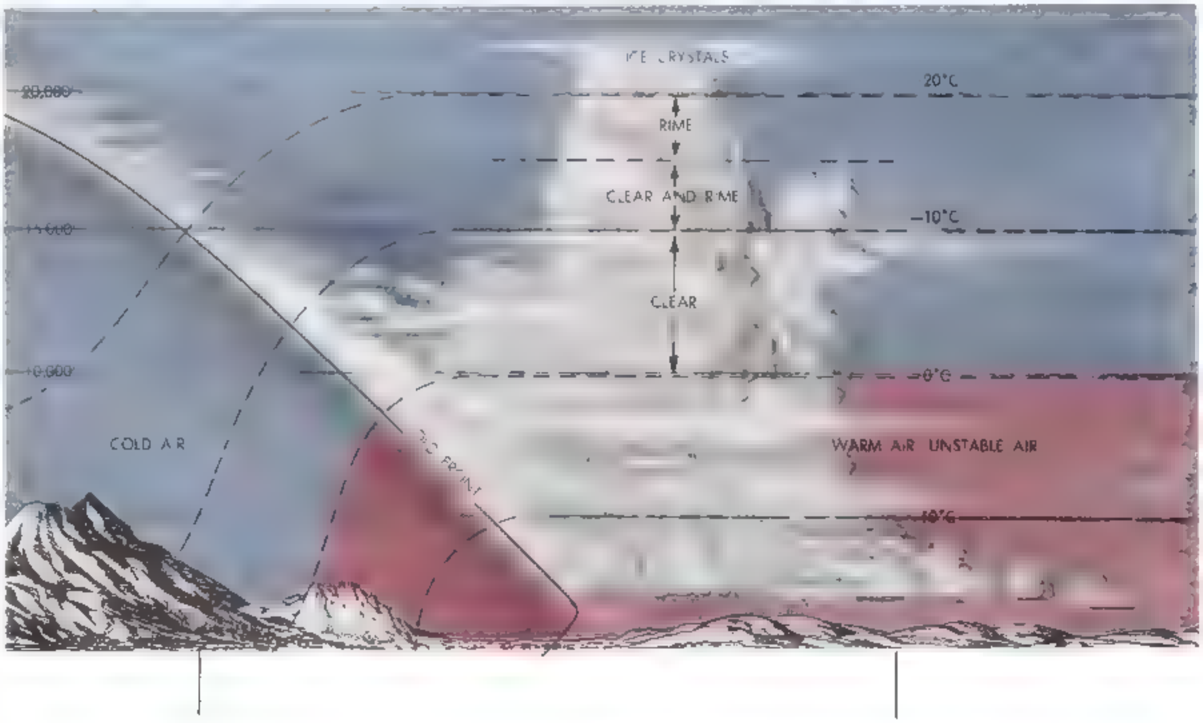


Figure 12-13. Cold Front Icing Zone.

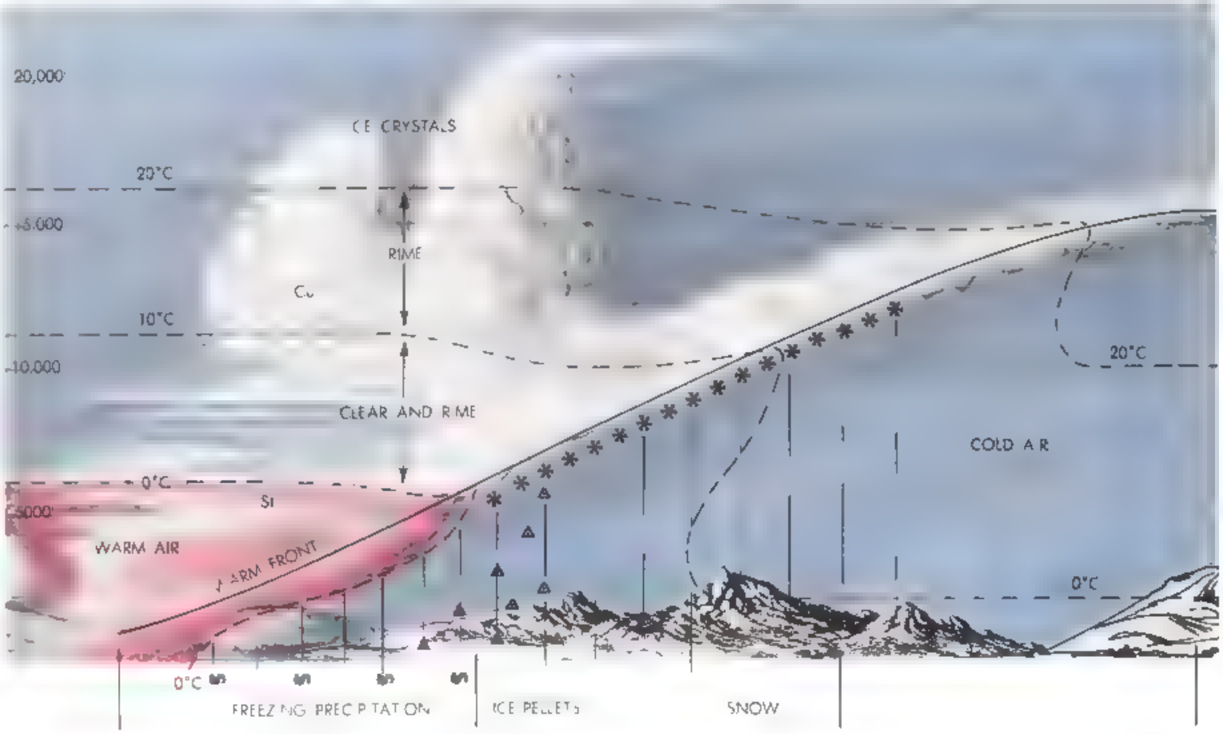


Figure 12-14. Warm Front Icing Zone.

For significant icing to occur above the frontal surface, the warm air must be lifted and cooled to saturation at temperatures below freezing, making it contain supercooled water. If the warm air is unstable, icing may be sporadic, if it is stable, icing may be continuous over an extended area. Icing may form in this manner over either a warm frontal or a shallow cold frontal surface. A line of showers or thunderstorms along a surface cold front may produce icing, but here the icing will be in a comparatively narrow band along the front.

Icing below a frontal surface outside of the clouds occurs most often in freezing rain or drizzle. Precipitation forms in the relatively warm air above the frontal surface at temperatures above freezing. It falls into the subfreezing cold air below the front, becomes supercooled, and subsequently freezes on impact with the aircraft. Freezing drizzle and rain occur with both warm fronts and shallow cold fronts. Icing in freezing precipitation is especially hazardous since it often extends horizontally over a broad area and can extend downward to the surface.

Seasons

Icing may occur during any season of the year, but in temperate climates, such as found in most of the United States, it is most frequent in the winter. The freezing level is nearer the ground in winter than in summer, leaving a smaller low-level layer of airspace free of icing conditions. Frontal activity also is more frequent in winter and the resulting cloud systems more extensive.

Geographic regions at higher latitudes, such as Canada and Alaska, generally have the most severe icing conditions in spring and fall. During winter the air is normally too cold in the polar regions to contain heavy concentrations of moisture necessary for icing, and most cloud systems are stratiform and composed of ice crystals.

Terrain

Icing is more probable and more severe in mountainous regions than over other terrain. Mountain ranges cause upward air motions on their windward side, and these vertical currents support large water droplets that would fall as rain over level terrain. The movement of a frontal system across a mountain range combines the normal frontal lift with the upslope effect of the mountains to create extremely hazardous icing zones.

The most severe icing occurs above the crests and to the windward side of the ridges (figure 12-15). This zone usually extends to about 5,000 feet above the tops of the mountains but can extend much higher when cumuliform clouds have developed

PROCEDURES TO AVOID OR MINIMIZE ICING EFFECTS

Aircrews must be prepared to avoid or to escape the icing hazard. The following procedures will help reduce the effects of icing on an aircraft·

- Remove all ice and snow from the aircraft before takeoff
- Use all necessary anti-ice/deice equipment.
- Avoid flying in clouds when the outside air temperature is between 0°C and -20°C
- If ice is encountered, climb or descend to an altitude where the temperature is warmer than 0°C or colder than -20°C.
- Send pilot reports if icing is encountered or if it is forecast and none is encountered.

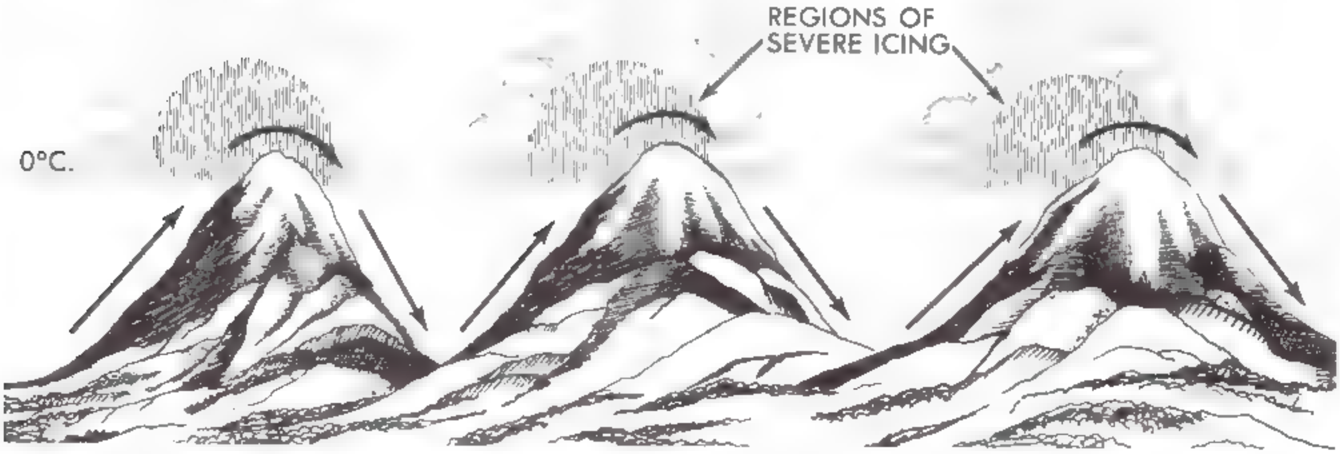


Figure 12-15. Icing Over Mountains.

CHAPTER 13

THUNDERSTORMS, LIGHTNING, AND ELECTROSTATIC DISCHARGE

THUNDERSTORMS

Thunderstorms contain many of the most severe atmospheric hazards to flight. They are almost always accompanied by strong wind gusts, severe turbulence, lightning, heavy rain-showers, and severe icing. During thunderstorms, hail is not uncommon and tornadoes are possible. Throughout this discussion, keep in mind that the terms thunderstorm, cumulonimbus, and Cb are synonymous. The only difference is the sound of thunder.

Obviously, thunderstorms should be avoided if possible. But with about 44,000 thunderstorms occurring daily over the surface of the earth, almost every aircrew can expect to encounter one occasionally. A knowledge of thunderstorm characteristics and the application of tested procedures will help the aircrew successfully fly through a thunderstorm area if no alternative course of action exists.

In some tropical regions, thunderstorms occur year-round. In the mid-latitudes, they develop most frequently in spring, summer, and fall. Arctic regions occasionally experience thunderstorms during summer.

Figure 13-1 shows the average number of days with thunderstorms each year in the United States. Note they are most frequent in the south central and southeastern states. The number of days a thunderstorm occurs varies from season to season as shown in figures 13-2 through 13-5. In general, thunderstorms in the United States are most frequent in July and August and least frequent in December and January

FACTORS NECESSARY FOR THUNDERSTORM DEVELOPMENT

The basic requirements for formation of a thunderstorm cloud (cumulonimbus) are unstable air, some type of lifting action, and high moisture content.

Unstable Air

Air that is potentially unstable will become unstable when it is lifted to a point where it becomes warmer than its surroundings. When this level has been reached, the warmer air continues to rise freely until, at some altitude, it has cooled to the temperature of the surrounding air

Lifting Action

Some type of external lifting action is necessary to bring the warm air from near the surface to the point where it will continue to rise freely (the level of free convection). The lifting action is normally provided by mountainous terrain, fronts, heating from below, or convergence (upward vertical motions associated with air coming together from different directions).

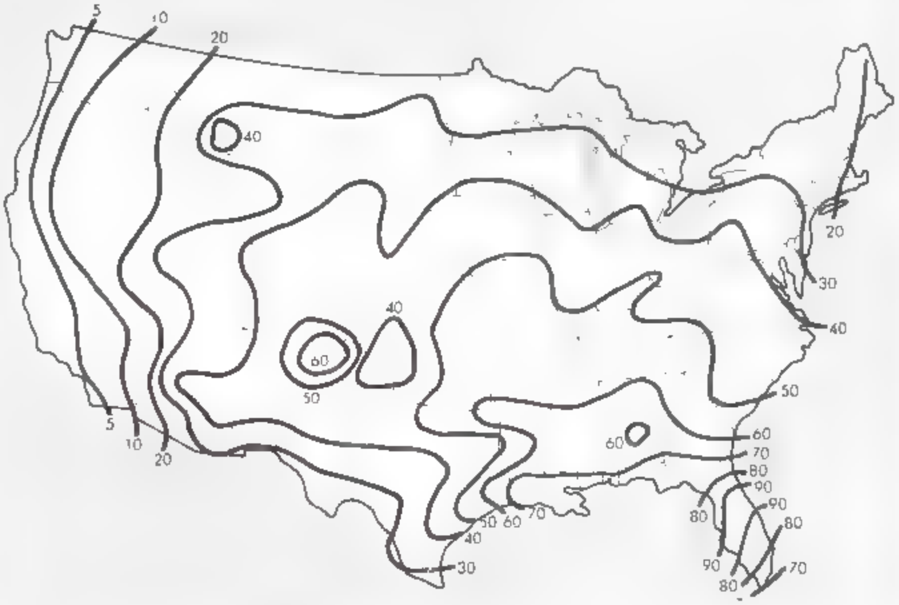


Figure 13-1. The Average Number Of Days With Thunderstorms Each Year.

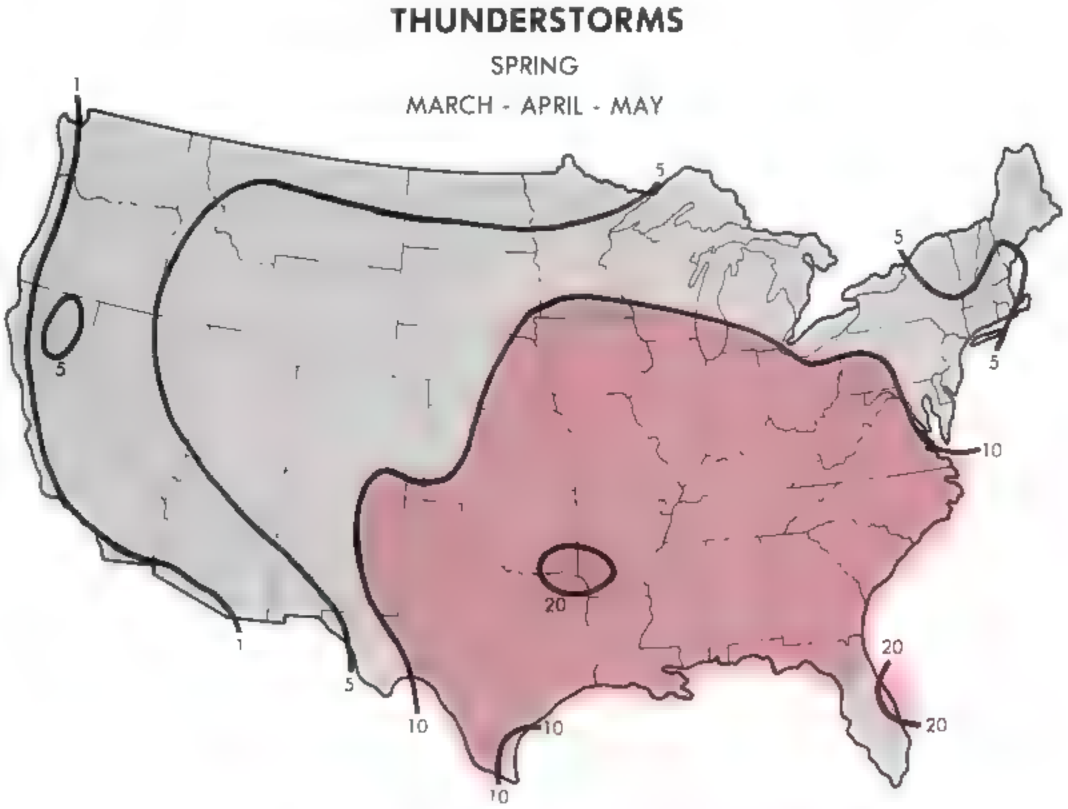


Figure 13-2. The Average Number Of Days With Thunderstorms During Spring.

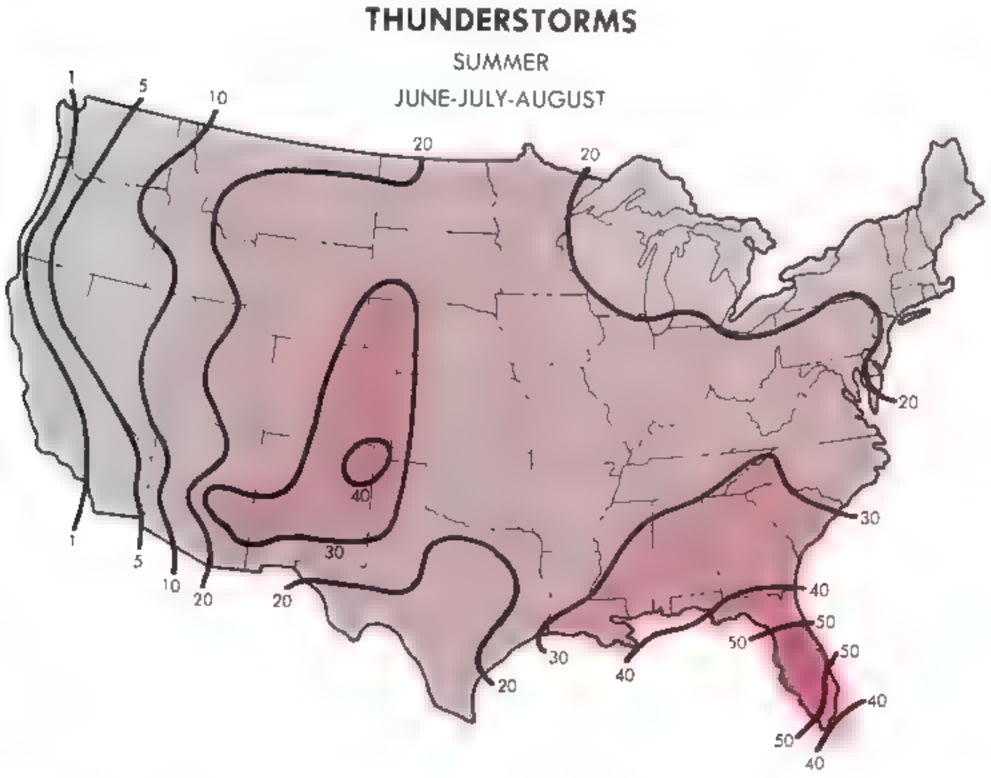


Figure 13-3. The Average Number Of Days With Thunderstorms During Summer.

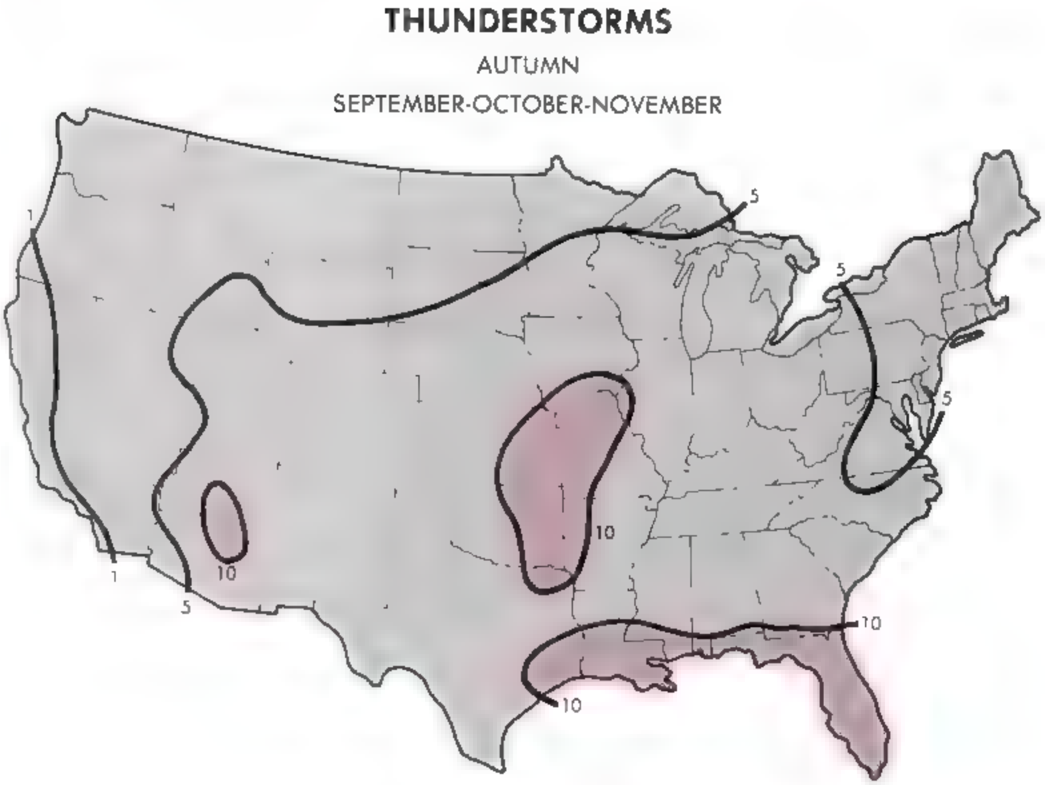


Figure 13-4. The Average Number Of Days With Thunderstorms During Fall.

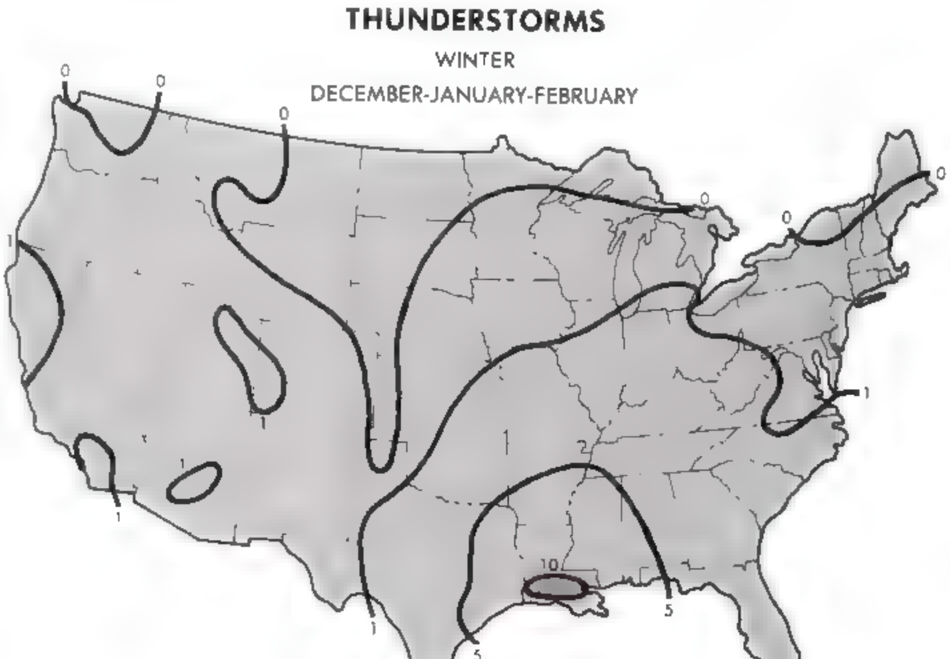


Figure 13-5. The Average Number Of Days With Thunderstorms During Winter.

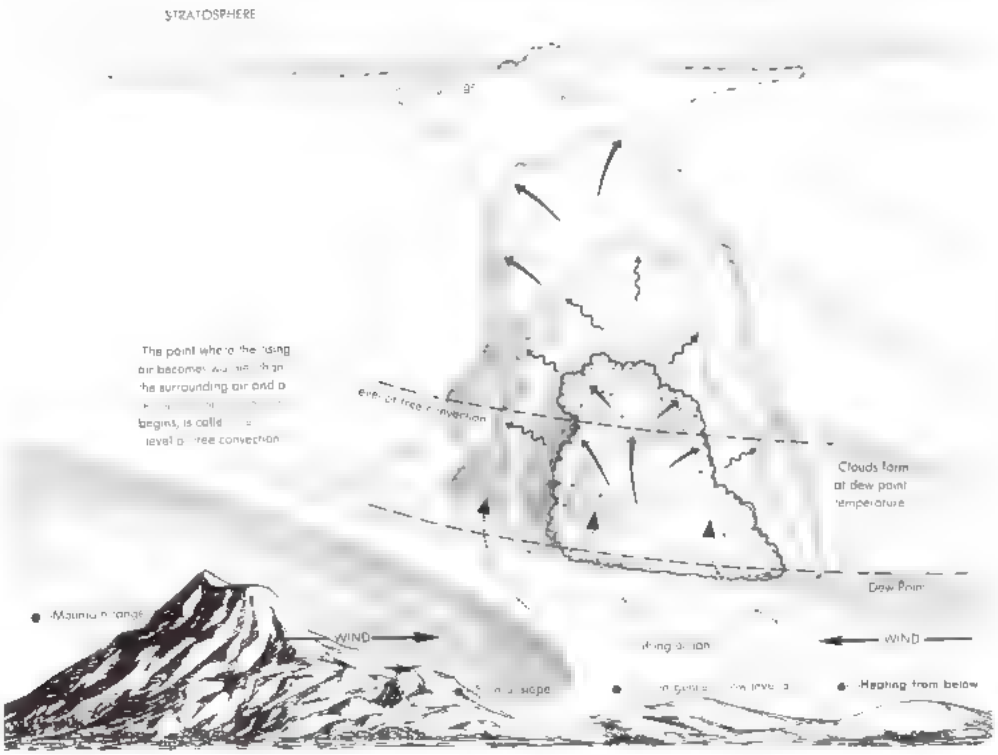


Figure 13-6. Lifting Mechanisms For Thunderstorm Development.

Moisture

Lifting of warm air will not necessarily cause free convection. Air may be lifted to a point where the moisture condenses and clouds form, but these clouds will not grow significantly unless the air is lifted to reach the level of free convection. The higher the moisture content, the easier the level of free convection is reached Once a cloud has formed, the latent heat of condensation (discussed in Chapter 2) released by the change of state from vapor to liquid tends to make the air more unstable

THE LIFE CYCLE OF THE THUNDERSTORM CELL

A thunderstorm cell during its life cycle progresses through three stages - cumulus (growth), mature, and dissipating. It is virtually impossible to visually detect the transition from one stage to another. Furthermore, a thunderstorm often may consist of a cluster of cells in different stages of the life cycle. The life cycle of each thunderstorm is from 20 minutes to three hours, depending on the number of cells contained and their stage of development.

Cumulus Stage

Although most cumulus clouds do not become thunderstorms, the initial stage of a thunderstorm is always a cumulus cloud. The main feature of the cumulus stage (figure 13-7A) is the updraft which may extend from near the earth's surface to several thousand feet above the visible cloud top. The greatest updraft occurs at higher altitudes late in this stage when it may reach 3,000 feet or more per minute.

As the cloud forms, water vapor changes to liquid and/or frozen cloud particles. This results in a release of heat (Chapter 2) that provides a source of energy for the developing cloud. Once the cloud has been formed by other forces, this release of heat helps keep it growing.

During this early period, cloud droplets are very small but grow into raindrops as the cloud builds upward. In the upper levels snow and ice particles exist, although raindrops remain as liquid in the updraft to heights well above the freezing level, even to 40,000 feet in some storms. There usually is no falling precipitation during this stage because the drops and ice particles are being carried upward, or being suspended, by the ascending air currents.

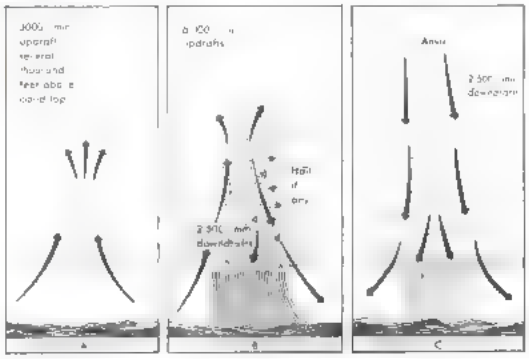


Figure 13-7. Stages Of A Thunderstorm.

Mature Stage

The beginning of rain or hail falling from the cloud-base indicates a downdraft has developed and the cell has entered the mature stage. The raindrops and ice particles in the cloud have grown too large to be supported by the updrafts. By this time the *average* cell has grown to a height of about 25,000 feet (although at high latitudes, tops may be as low as 12,000 feet).

As the drops begin to fall, the surrounding air begins a downward motion. Since it is unstable, the cold air accelerates forming a *downdraft* which may reach a velocity of 2,500 feet per minute (figure 13-7B). The downdraft spreads outward near the surface, producing a sharp temperature drop and strong, gusty, surface winds. The leading edge of this wind is called the *gust front*

Early in the mature stage, remaining updrafts continue to increase in speed. They may exceed 6,000 feet per minute. Updrafts and downdrafts near each other create strong, vertical shear and therefore severe turbulence. All thunderstorms reach their greatest intensity at this time.

Dissipating Stage

Throughout the mature stage, the downdrafts continue to develop while the updrafts are continually weakening. As a result, the entire thunderstorm cell ultimately becomes an area of downdrafts (figure 13-7C). Since updrafts are necessary to produce condensation and latent heat energy, the thunderstorm begins to dissipate. During this stage, strong winds aloft may carry the upper section of the cloud into the familiar anvil form (figure 13-8). However, appearance of the anvil is not in itself evidence that the thunderstorm system has dissipated. Severe weather can still be found in many storms with a well developed anvil.

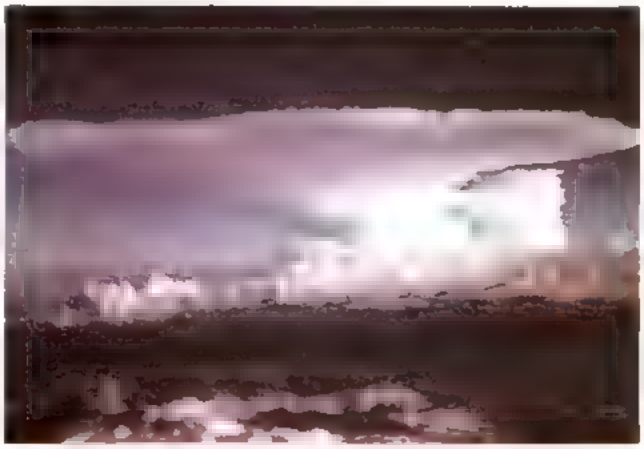


Figure 13-8. Thunderstorm With A Well Developed Anvil.

The more severe thunderstorm occasionally does not dissipate in the manner described above. If horizontal wind speeds increase markedly with height, the mature stage is prolonged, and considerable tilt develops in the updraft and cloud. In this situation, precipitation falls through only a small portion of the rising air and later falls through the relatively still air near the updraft, or perhaps completely outside of the cloud (figure 13-9).

In this situation, the updrafts in the cloud can continue until their source of energy is exhausted. The thunderstorm may dissipate without going through a period in which the principal vertical motion is downward. Furthermore, precipitation falling from the tilted cloud may produce downdrafts in the clear air outside the cloud boundary.

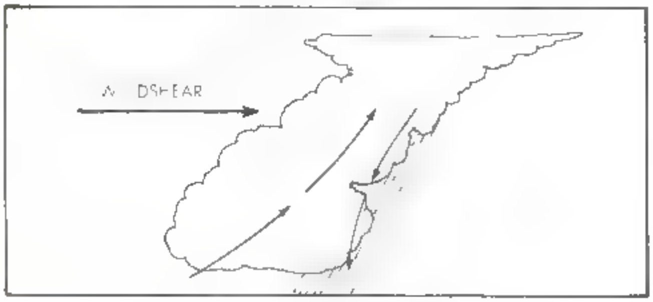


Figure 13-9. Prolonged Mature Stage.

TYPES OF THUNDERSTORMS

Frontal Thunderstorms

Thunderstorms may occur within the cloud system of any front - warm, cold, stationary, or occluded. Frontal thunderstorms are caused by the lifting of warm, moist, unstable air over a frontal surface. Thunderstorms may also occur many miles ahead of a rapidly moving cold front.

Because of the gentleness of the frontal slope, stratiform clouds are likely to accompany *warm fronts*, and thunderstorms may be obscured unless the aircrew is flying above the stratiform layer. If flying at low levels, the aircrew may be forewarned of such a condition by loud crashes of static in their earphones. Because of the shallow slope of the warm front, warm-front thunderstorms are usually the least severe of all frontal thunderstorms (figure 13-10).

Figure 13-10. Warm Front Thunderstorm.

Thunderstorms associated with *cold fronts* are normally the most severe ones found anywhere except in squall-lines. They usually form in a continuous line and are easy to recognize. These thunderstorms are usually most active during the afternoon (figure 13-11)

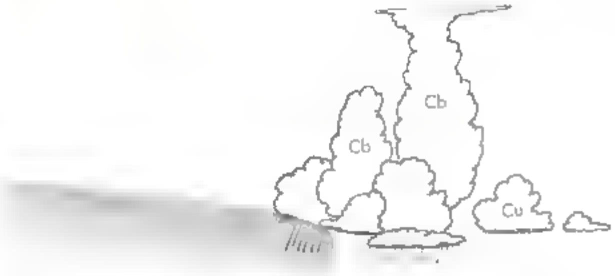


Figure 13-11. Cold Front Thunderstorm.

Thunderstorms may occasionally develop along a *stationary front.* Thunderstorms along the stationary front are normally widely scattered.

Thunderstorms are also associated with *occluded fronts.* These thunderstorms are particularly dangerous to aircrews because they are not only well developed, but they are embedded in stratiform clouds and can be difficult to see.

Squall-Line Thunderstorms

A *squall-line* is a nonfrontal, narrow band of active thunderstorms Often it develops 50 to 300 miles ahead of a rapidly moving cold front in moist, unstable air (figure 13-12), but the existence of a front is not a prerequisite The line may be too long to easily detour and too wide or severe to penetrate

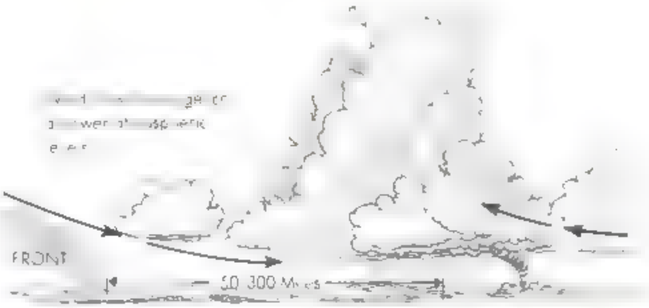


Figure 13-12. Squall Line.

Squall-line thunderstorms usually form rapidly and are usually more violent than cold-front thunderstorms. The most severe conditions, such as heavy hail, destructive winds, and tornadoes, are generally associated with squall-line thunderstorms. Figure 13-13 is a photograph of an advancing squall-line

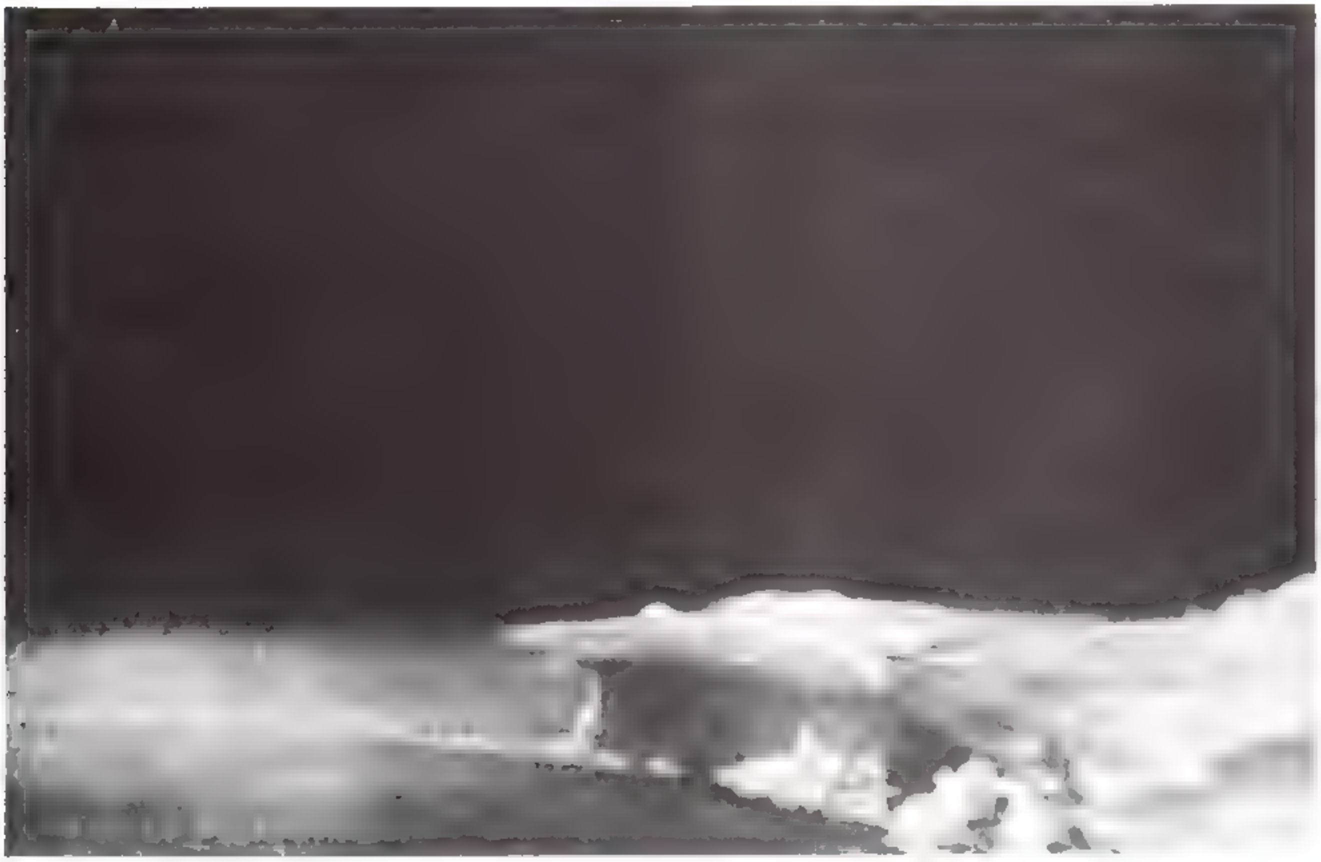


Figure 13-13. Squall Line Thunderstorms.

Air-Mass Thunderstorms

Air-mass thunderstorms form within a warm, moist air mass, but are not associated with a front. They are generally isolated or widely scattered over a large area. These thunderstorms receive their necessary lift by heating from below (convection), convergence of the low-level wind flow, or winds forcing the moist, unstable air up mountain slopes (figure 13-14).

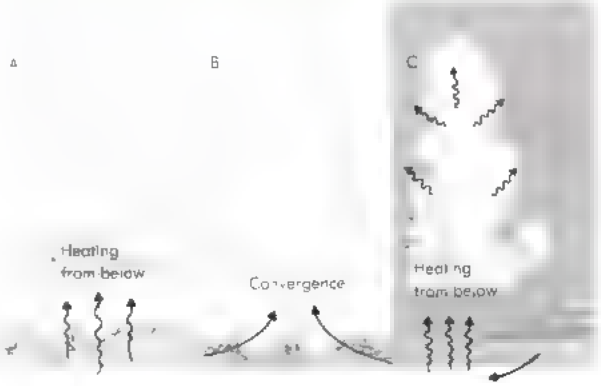


Figure 13-14. Air Mass Thunderstorm.

Since air-mass thnderstorms generally result from surface heating and convergence, they reach maximum intensity and frequency over land during middle and late afternoon. Along coastal regions they reach a maximum during the night and early morning when the cool air flowing off the land is heated by the warmer water surface, causing thunderstorms to form a short distance offshore.

Thunderstorms will form on the windward side of a mountain if the wind forces moist, unstable air up the slope. These are termed *orographic thunderstorms*. The storm activity is usually scattered along the individual mountain peaks, but occasionally there will be a long, unbroken line of thunderstorms. Stratus and stratocumulus clouds frequently enshroud the mountain peaks and obscure the storm (figure 13-15).

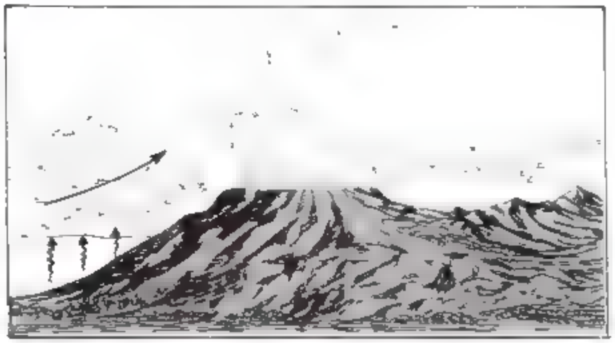


Figure 13-15. Orographic Thunderstorm.

THUNDERSTORM WEATHER HAZARDS

Thunderstorms and cumulonimbus clouds may be accompanied by extreme turbulence, icing, lightning, precipitation, and gusty surface winds. The more severe thunderstorms produce hail and sometimes tornadoes.

Turbulence

Hazardous turbulence is present in all thunderstorms, and in a severe thunderstorm it can damage an airframe and cause serious injury to passengers and crew. The strongest turbulence within the cloud occurs with shear between updrafts and downdrafts. Outside the cloud, shear turbulence has been encountered several thousand feet above and 20 miles laterally from a severe storm. Severe turbulence can be encountered in the anvil 15 to 30 miles downwind (figure 13-16). Remember, the storm cloud is only the visible portion of a turbulent system whose updrafts and downdrafts often extend outside the storm proper.

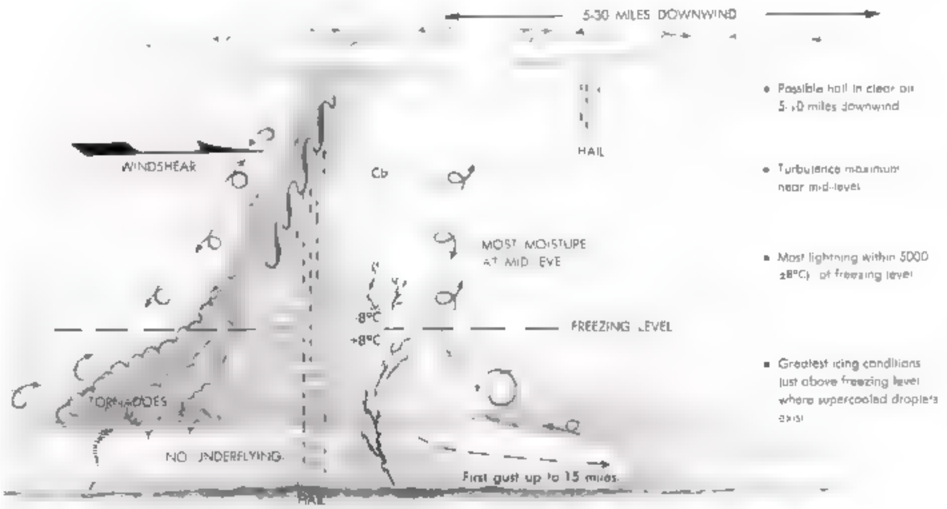

5-30 MILES DOWNWIND
HAIL
WINDSHEAR
Cb
MOST MOISTURE AT MID LEVEL
-8°C
+8°C
FREEZING LEVEL
TORNADOES
NO UNDERFLYING
First gust up to 15 miles
HAIL
• Possible hail in clear air 5-30 miles downwind
• Turbulence maximum near mid-level
• Most lightning within 5000 (±8°C) of freezing level
• Greatest icing conditions just above freezing level where supercooled droplets exist

Figure 13-16. Typical Location Of Thunderstorm Turbulence.

A low-level turbulent area is the shear zone between the cold air downdraft and surrounding air. This occurs often up to 10 or 15 miles ahead of a mature storm and is called the *gust front*. At times second or third gust fronts are found between the first gust front and the thunderstorm base due to multiple downdrafts in the storm. Horizontal wind direction averages a 40 percent change of direction across the gust front, and wind speed may increase as much as 50 percent between the surface and 1,500 feet. Thus, the surface observation may not give a true estimate of the actual wind just above the surface (figure 13-17).

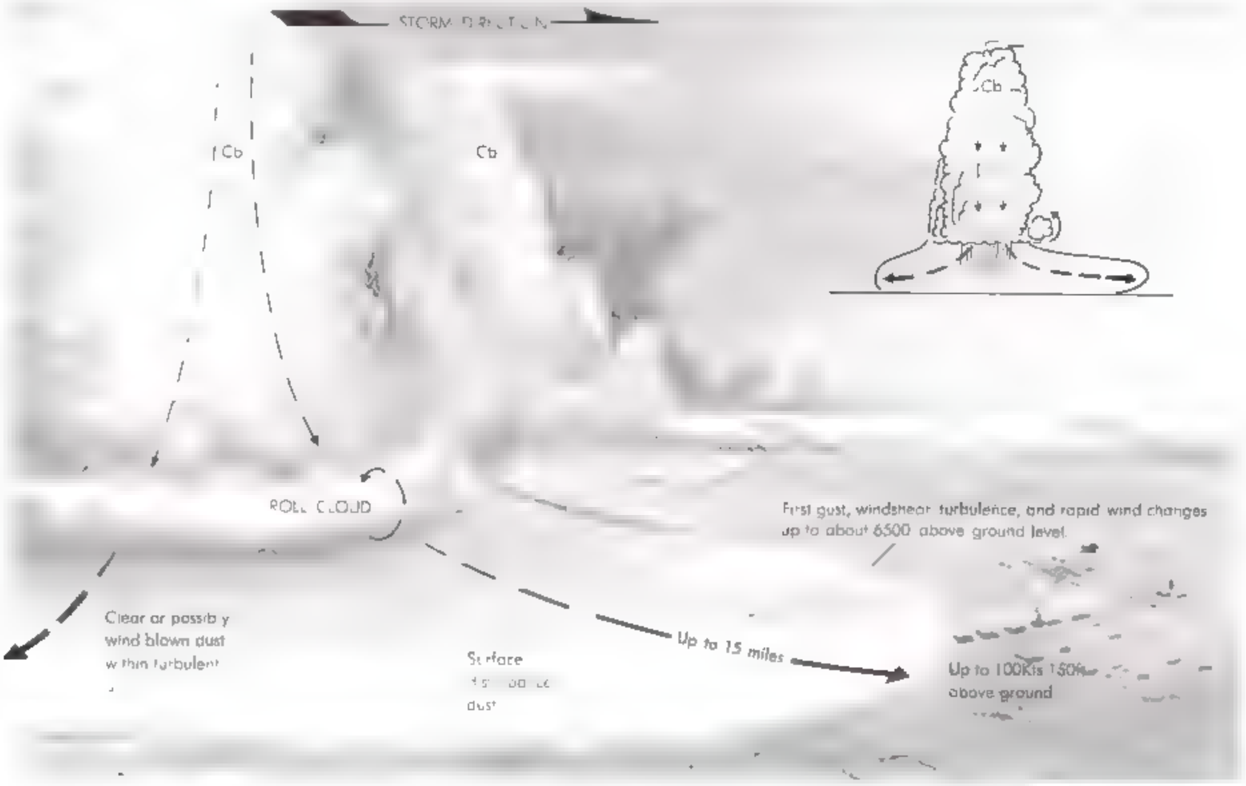

STORM DIRECTION
Cb
Cb
Cb
ROLL CLOUD
First gust, windshear turbulence, and rapid wind changes up to about 6500 above ground level.
Clear or possibly wind blown dust within turbulent
Surface
dust
Up to 15 miles
Up to 100Kts 150ft above ground

Figure 13-17. First Gust Hazards.

Often a "roll cloud" on the leading edge of a storm marks the eddies to this shear (figure 13-17). The roll cloud is most prevalent with cold front or squall-line thunderstorms and indicates an extremely turbulent zone.

Hail

Hail is regarded as one of the worst hazards of thunderstorm flying. It usually occurs during the mature stage of cells having a strong updraft. As a rule, the larger the storm, the more likely it is to have hail. Hail has been encountered as high as 45,000 feet in completely clear air and may be carried up to 10 miles downwind from the storm core. Aircrews should anticipate possible hail with any thunderstorm, especially beneath the anvil of a large cumulonimbus.

Hailstones larger than one half to three-quarters of an inch can cause significant aircraft damage in a few seconds (figure 13-18). Figure 13-19 shows photographs of aircraft which have flown through hail.

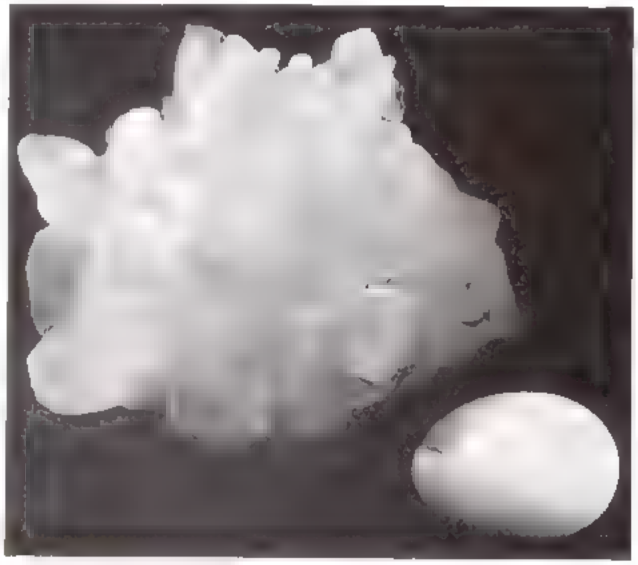


Figure 13-18. Large Hail.

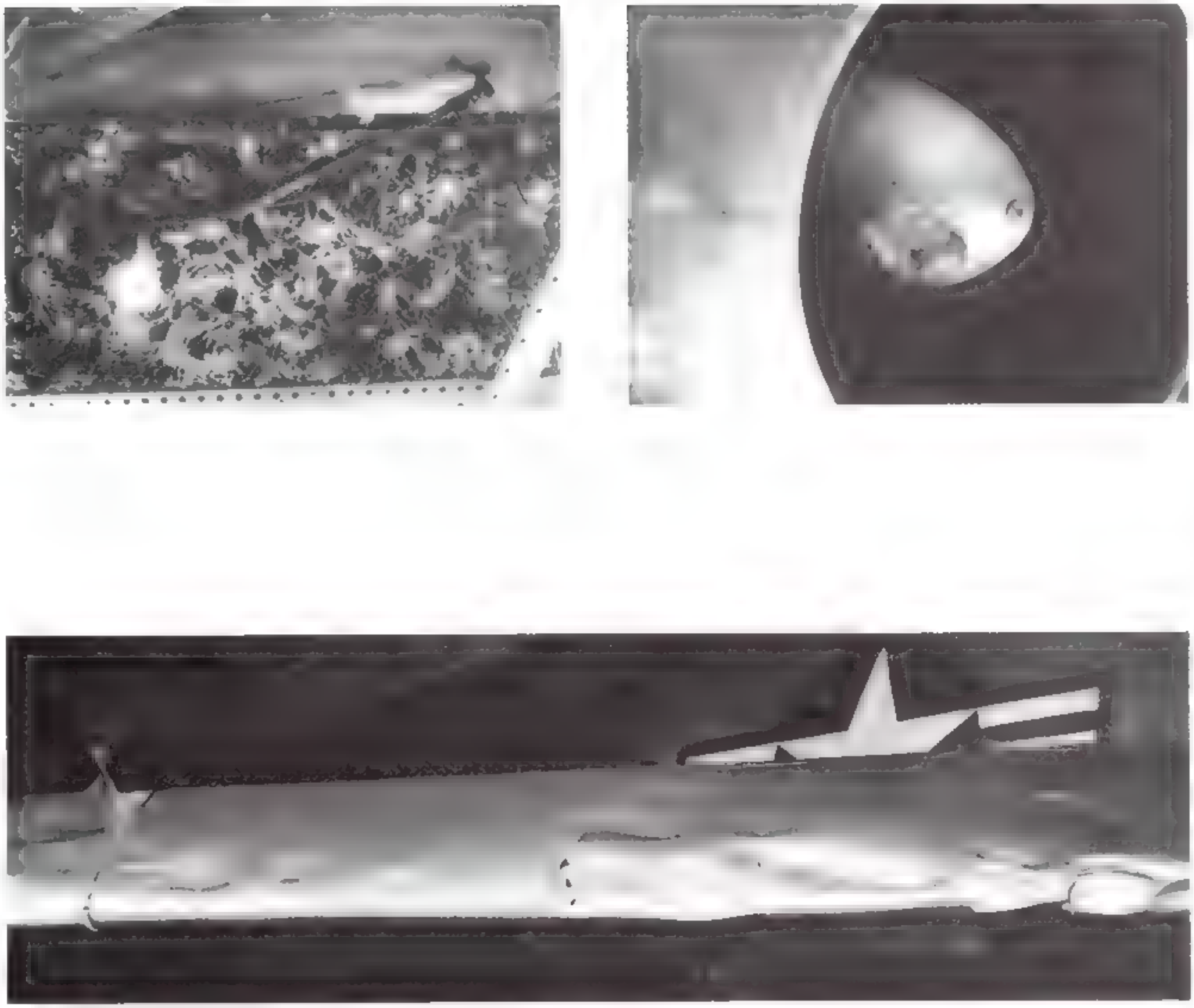


Figure 13-19. Hail Damage To Aircraft.

Icing

Where the free-air temperatures are at or below freezing, icing should be expected (figure 13-20). In general, icing is associated with temperatures from 0°C to -20°C. The most severe icing occurs from 0°C to -10°C, while the heaviest icing conditions usually occur just above the freezing level. Since the freezing level is also the zone where heavy rainfall and turbulence most frequently occur, this particular altitude appears to be the most hazardous

LIGHTNING AND ELECTROSTATIC DISCHARGE

Lightning occurs at all levels in a thunderstorm. The majority of lightning discharges never strike the ground but occur between clouds or within the same cloud (figure 13-21). However, aircrews flying several miles from a thunderstorm can still be struck by the proverbial "bolt out of the blue" (figure 13-22). Electrical activity generated by a thunderstorm may also continue to exist even after the thunderstorm itself has decayed This electrical activity may drift downstream and is usually found within the cirrus deck that at one time was connected to the thunderstorm cell.

Figure 13-20. Aircraft Icing.

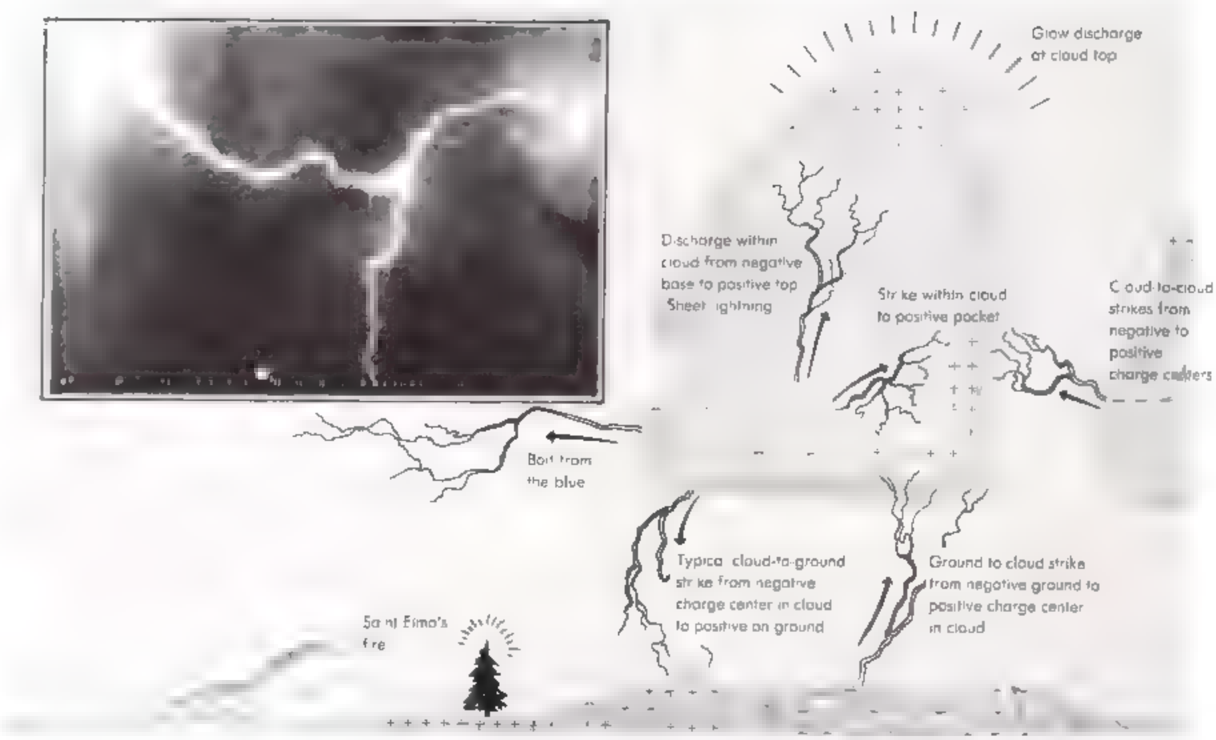

Glow discharge at cloud top
Discharge within cloud from negative base to positive top Sheet lightning
Strike within cloud to positive pocket
Cloud-to-cloud strikes from negative to positive charge centers
Bolt from the blue
Typical cloud-to-ground strike from negative charge center in cloud to positive on ground
Ground to cloud strike from negative ground to positive charge center in cloud
Saint Elmo's Fire

Figure 13-21. Lightning Variations.

A charge also may build up on an aircraft after it has been flying through clouds and precipitation, including snow as well as rain, or solid particles such as dust, haze, and ice. The larger the aircraft and the faster it flies, the more particles it impacts, generating a greater charge on the aircraft. The electrical field of the aircraft may interact with the cloud and an *electrostatic discharge* may then occur. Electrostatic discharges usually cause only minor physical damage and indirect effects, such as electrical circuit upsets

Aircraft Lightning or Electrostatic Discharge Encounters

Lightning strikes and electrostatic discharges are the leading causes of reportable weather-related aircraft accidents and incidents in the Air Force. All types of aircraft are susceptible to lightning strikes and electrostatic discharges. Aircraft have been struck by lightning or experienced electrostatic discharges at altitudes ranging from the surface to at least 43,000 feet. Most lightning strikes occur when aircraft are operating in one or more of the following conditions.

- Within 8°C of the freezing level.
- Within about 5,000 feet of the freezing level
- In precipitation, including snow.
- In clouds
- In some turbulence

It should be noted that all the conditions do not have to occur for a lightning strike or an electrostatic discharge to take place.

Lightning strikes have varied effects on aircraft and aircrews. Usually the structural damage is minor (figure 13-23). However, lightning strikes can also cause more severe structural damage to aircraft (figure 13-24)

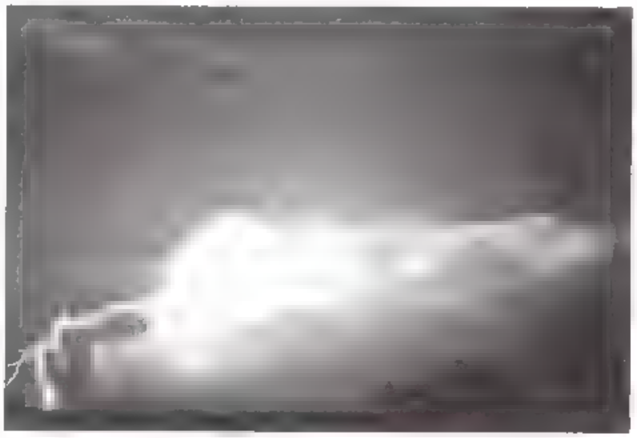


Figure 13-22. Lightning "Bolt Out Of The Blue".

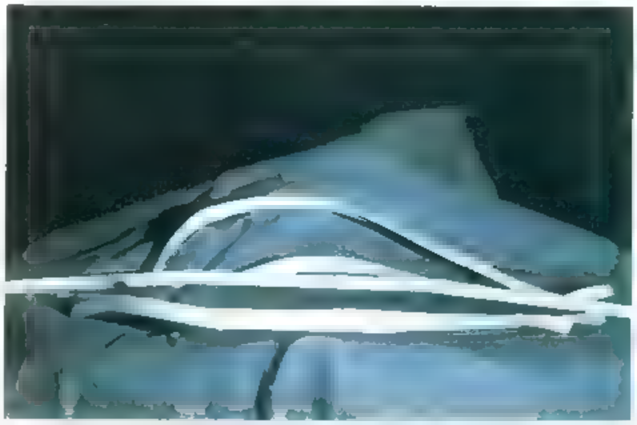


Figure 13-23. FB-III Pitot Tubes After Being Struck By Lightning.

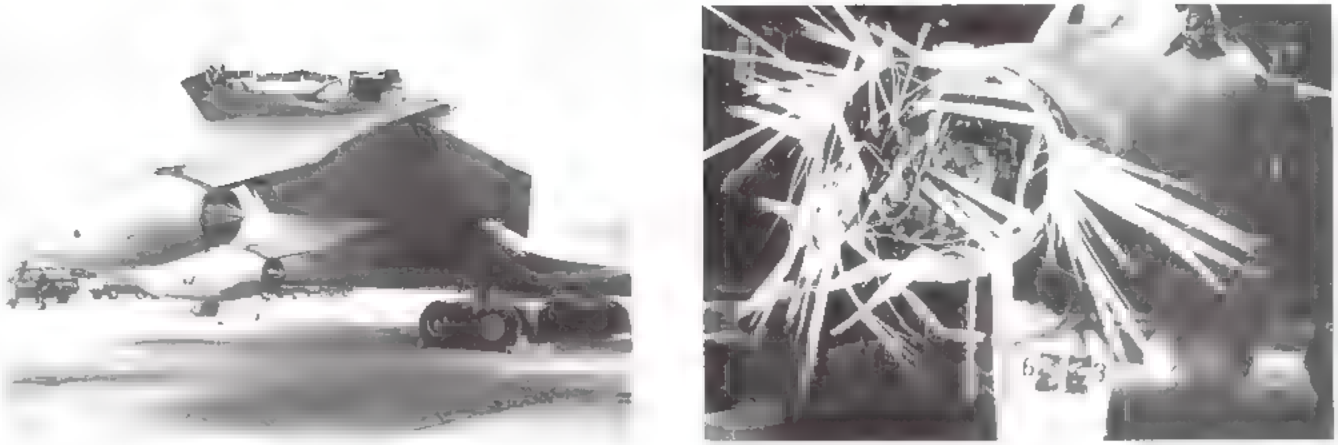


Figure 13-24. Major Aircraft Structural Damage Resulting From Lightning Strike.

Damage to aircraft electrical systems instruments avionics, and radar is also possible Transient voltages and currents induced in the aircraft electrical systems, as well as direct lightning strikes, have caused bomb doors to open, activated wing folding motors, and made the accuracy of electronic flight control navigational systems questionable. After a lightning or electrostatic discharge encounter, all instruments should be considered invalid until proper operation is verified

Under certain conditions, catastrophic fuel ignition can occur. The space above the liquid fuel in most aircraft fuel tanks is filled with a mixture of vaporized fuel and air. The proper ratio of fuel vapor to air forms a highly explosive mixture. Figure 13-25 shows the approximate temperature-altitude range in which three standard fuels result in explosive mixtures

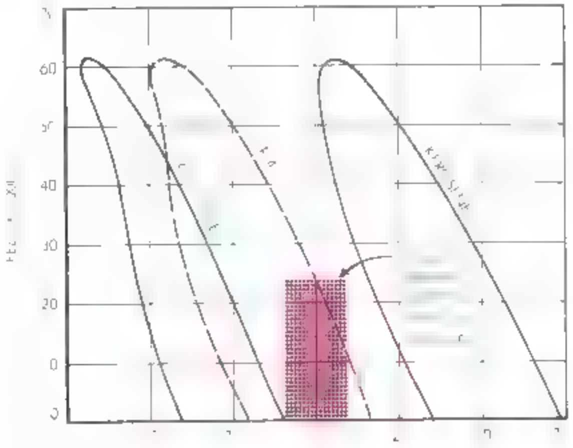


Figure 13-25. Temperature-Altitude Ranges Of Explosive Fuel Mixtures.

As noted earlier, the majority of lightning strikes to aircraft occurs between +8 and -8°C shown as the red area of figure 13-25. JP-4 vapor forms nearly an ideally explosive mixture, and there appears little question that, in general, JP-4 is significantly more vulnerable to explosion than either gasoline or kerosene.

Aircrews are not immune to the effects of lightning strikes either. Flash blindness can last up to 30 seconds, and the shock wave can cause some temporary hearing loss if headphones or some form of hearing-loss protection gear is not worn Some aircrews have even experienced a mild electric shock and minor burns

TORNADOES

Tornadoes are violent, rotating columns of air that descend with a familiar funnel or tube-shape from a cumulonimbus cloud (figure 13-26). If the cloud does not reach the surface, it is called a *funnel cloud* (figure 13-27); if it touches water, it is called a *water spout* (figure 13-28). A tornado vortex is normally several hundred yards wide.

Figure 13-26. A Toronado.

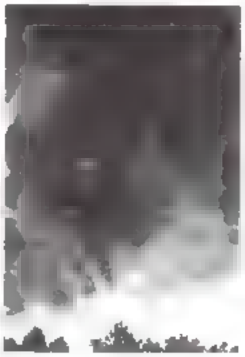


Figure 13-27. Funnel Clouds.

Figure 13-28. A Waterspout.

Within the tornado's funnel-shaped cloud, winds can attain speeds up to 300 miles per hour, while the forward speed of the tornado averages only 40 knots

Tornadoes occur with isolated thunderstorms at times, but much more frequently they form with thunderstorms associated with fast moving cold-fronts or squall-lines

Families of tornadoes or tornadic vortices have been observed as appendages of the main cloud, extending 20 miles outward from the area of lightning and precipitation (figure 13-29). They may last from a few minutes up to six hours in duration These vortices usually occur on the southern or south western flank of the storm. Tornadic vortices can be masked by innocent-looking cumulus clouds trailing the thunderstorm and may or may not be visible to alert the unwary crew member. The invisible vortices may only be evidenced by swirls in the cloud-base or dust-whirls boiling along the ground, but may be strong enough to cause severe structural damage to the aircraft

Do not fly below lines of clouds extending from an intense thunderstorm. If inadvertently caught under one of these lines, watch for dust-whirls and avoid overflying them as you quickly exit the area. Seek additional help from ground-based radar if available.

Airborne radar isn't much help in spotting tornado locations. It returns echo areas of significant precipitation and doesn't display a spinning column of

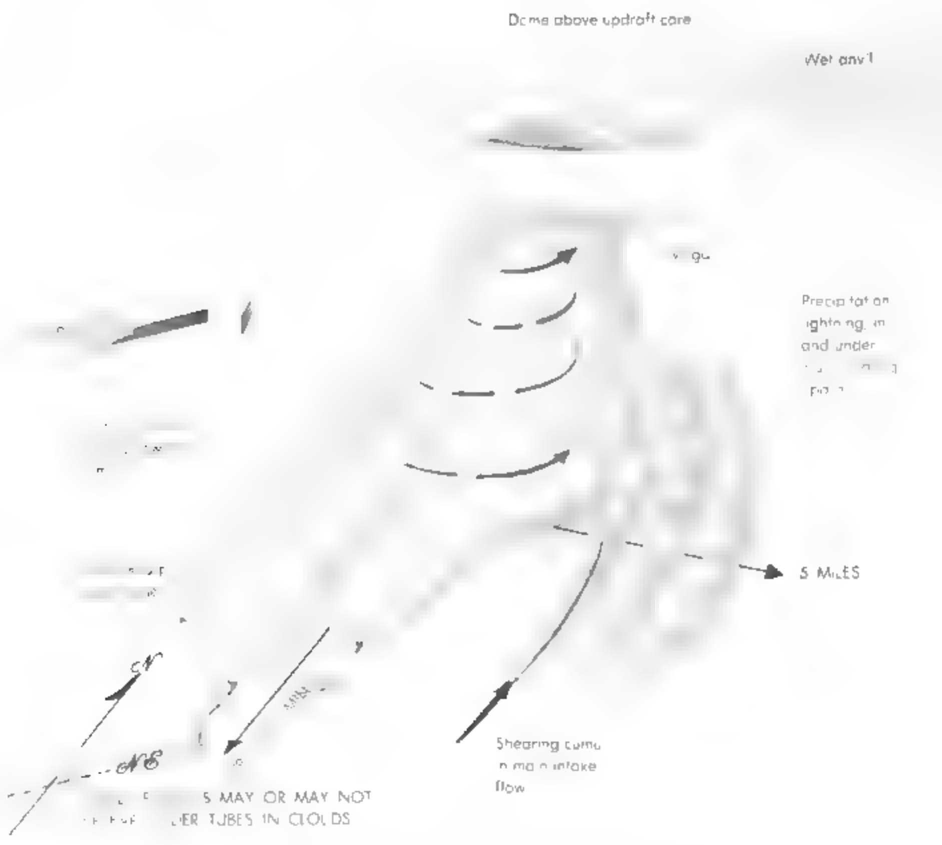


Figure 13-29. Tornado Funnel Cloud.

air for your guidance while flying around the thunderstorms. It must be emphasized that just plain eyeballing and radar scanning a line of CB's won't tell you which thunderstorm is hiding a tornado. Caution is advised on landing and takeoff, and descent and climbout under or through lines of thunderstorms. The hazard tends to increase with altitude in the clouds because of the convergence of the vortices upward in the cloud line (figure 13-30). The effect upon the aircraft may range from a thump in a grazing incident to a catastrophic airframe failure in major internal encounters.

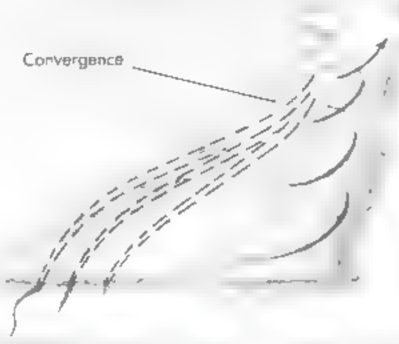


Figure 13-30. Funnel Convergence.

THUNDERSTORM EFFECT ON ALTIMETERS

Pressure usually falls rapidly with the approach of a thunderstorm, rises sharply with the onset of the gust front and rain-showers, and returns to normal as the storm moves on. Such rapid pressure changes may result in significant altitude errors if the altimeter setting of a landing aircraft is not corrected

PRECIPITATION STATIC

Precipitation static is a steady, high level of noise in radio receivers caused by intense, continual corona discharges from sharp metallic points and edges of flying aircraft. It is encountered often in the vicinity of thunderstorms. When an aircraft flies through an area which contains clouds, precipitation, or a concentration of solid particles (ice, sand, dust, and such), it accumulates a charge of static electricity. The electricity discharges onto a nearby surface, or into the air, causing a noisy disturbance at lower radio frequencies. Usually precipitation static does not interfere with reception on ultra-high frequencies.

A corona discharge is weakly luminous and may be seen at night under certain conditions. In itself, it is harmless. It was named *St. Elmo's fire* by Mediterranean sailors who frequently saw the brushy discharge at the top of ship masts.

THUNDERSTORM AND LIGHTNING FLYING PROCEDURES

There are no hard, fast rules which govern all flights influenced by thunderstorms and lightning. Most flight manuals contain a section which outlines speeds, configurations, and techniques which are best for flying through lightning and thunderstorm areas. *The procedures in this weather manual are generalized and should not be used to supersede the flight manual.*

When making a decision to fly through a thunderstorm area, you should take into consideration the following factors: mission priority, aircraft type and performance, radar availability and maintenance status, aircrew experience, and the horizontal and vertical extent of the thunderstorm. The best policy to follow is to AVOID ALL THUNDERSTORMS If you *must* penetrate a storm area, comply with thunderstorm avoidance rules in AFR 60-16 and follow the general flight procedures listed below.

- Before actual penetration, use your airborne radar and call the nearest pilot to metro service (PMSV) with weather radar. The ground radar can measure tops and reflectivity factors, which the airborne radar cannot (see Attachment 1).
- Get your aircraft ready for thunderstorm penetration prior to entry by checking instrument and cockpit lights full bright, pitot heat on, and safety belts and shoulder harnesses tightened and locked. Change power settings to establish the recommended airspeed. This airspeed will reduce the hazard of exceeding stress limitations and improve control capability. Choose a heading that will minimize travel time in the storm
- Maintain a constant *attitude* DO NOT chase the altitude Trying to maintain a constant altitude during storm updrafts and downdrafts increases stress on the aircraft.
- Do not fly under the cirrus anvil. Hail damage can be severe here.
- Do not penetrate the storm near the freezing level. Most of the worst thunderstorm hazards occur in the temperature range 8 C to +8 C.
- After penetration, avoid unnecessary maneuvering. Do not turn around. Attempting to do so will keep you in the storm longer, increase stress on the aircraft, and increase the possibility of stall.
- After clearing the storm, give a pilot report (PIREP) to PMSV or your controlling agency But remember, if you received a PIREP from someone else, a thunderstorm can change in character in less than 10 minutes

To reduce the risk of encountering lightning or an electrostatic discharge, comply with MAJCOM thunderstorm avoidance rules and follow these general flight procedures:

- Avoid penetrating the thicker regions of cirrus decks that were once associated with thunderstorms. Electrical activity generated by a thunderstorm may exist even after the thunderstorm cell has decayed
- Avoid prolonged flight in precipitation or clouds.
- Do not loiter near the freezing level, especially during climb and descent since most lightning strikes occur within 8°C of the freezing level Use steep climbs and descents where possible
- During formation flights, fly single ship or radar trail in areas where lightning strike potential is high. Lightning has been known to strike several formation aircraft simultaneously

CHAPTER 14

RESTRICTIONS TO VISIBILITY

Statistics show that low ceilings and poor visibilities contribute toward many aircraft accidents. Fog and/or low stratus clouds prevent navigation by visual reference more often than any other weather phenomenon. However, fog and low stratus are not the only restrictions to visibility. Other phenomena which are also rather common occurrences are included in this chapter.

VISIBILITY

Meteorological visibility is the greatest horizontal distance at which selected objects can be seen and identified by unaided eyes. Since this distance is not always the same in all directions, the *prevailing visibility* is reported at most weather stations. Prevailing visibility is defined as the greatest horizontal visibility observed throughout at least half of the horizon circle. It need not be a continuous half. It is prevailing visibility which determines whether flights are permissible under visual flight rules (VFR) or instrument flight rules (IFR). Also, prevailing visibility is used for circling approaches. It is the only forecast visibility.

Aircrews making approaches for landing are concerned with still another type of visibility. This is the distance from which the aircrew on final approach can see landing aids on the ground. It is called *slant range visibility*.

Another visibility value of interest to the crew is the *runway visual range* (RVR). It is an instrumentally or visually derived value that represents the horizontal distance an aircrew will see down the runway from the approach end.

Crew members should bear in mind that the prevailing visibility, slant range visibility, and runway visual range may differ from each other on many occasions. The term "visibility" as used throughout this chapter refers to horizontal surface visibility unless it is stated otherwise.

CEILING

Ceiling is defined as the height above the earth's surface of the lowest layer of clouds or obscuring phenomenon that is reported as broken, overcast, or totally obscured. It does not include such classifications as thin or partly obscured. The percentage of hours when the ceiling is below 1,000 feet and the visibility is less than three miles in the contiguous United States is given for the four seasons in figure 14-1.

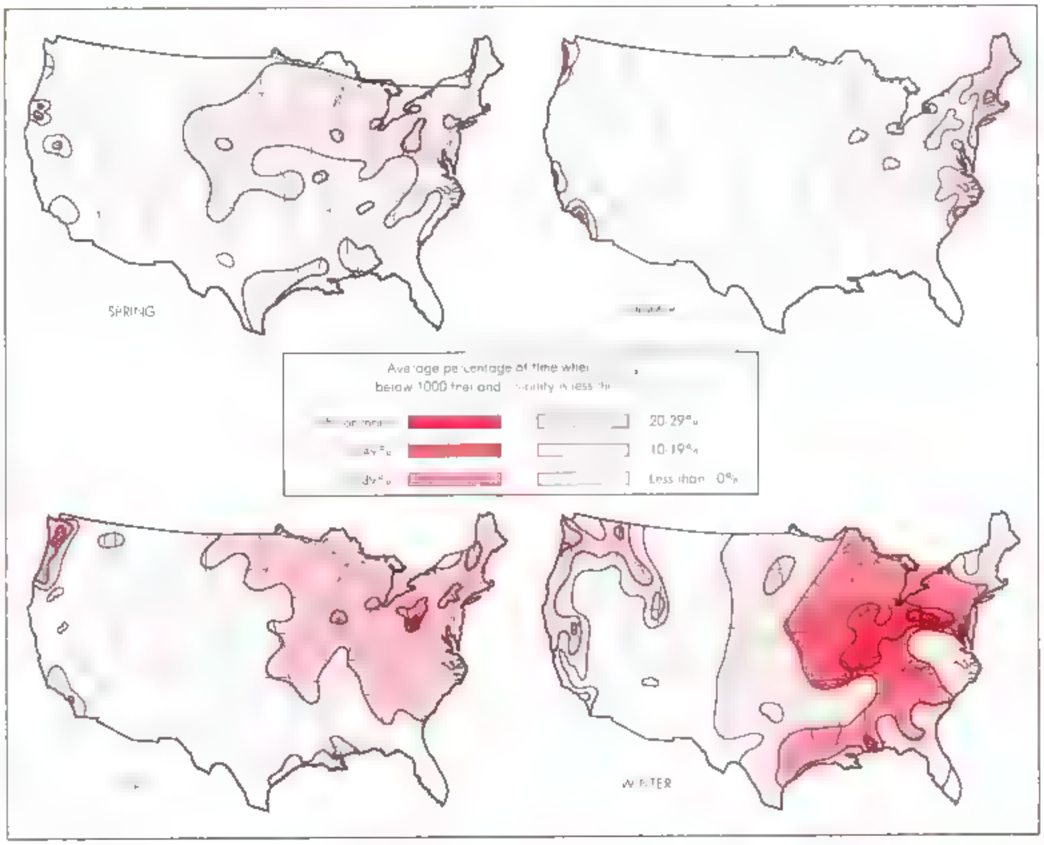

SPRING
Average percentage of time when
below 1000 feet and visibility is less th
20-29%
10-19%
Less than 10%
WINTER

Figure 14-1. Seasonal Restrictions To Visibility.

Obscured Sky

To be classified as obscuring phenomena, precipitation, smoke, haze, fog, or other visibility restricting conditions must extend upward from the surface. When the sky is totally hidden from an observer on the ground, the sky is termed *obscured*. The ceiling will be reported as the vertical visibility from the ground upward into the obscuration. For example, when the sky is totally hidden by smoke and the ground observer can see upward for 600 feet, the ceiling will be reported as indefinite at 600 feet

It is important to note the difference between the obscuration ceiling of 600 feet in the foregoing example and a cloud ceiling of 600 feet. With a low cloud ceiling, the aircrew normally can expect to see the ground and the runway after descending to a level below the cloud base. However, with an obscured ceiling, the obscuring phenomenon restricts visibility between the aircraft altitude and the ground, and the *slant range visibility* is greatly reduced. The aircrew normally will not be able to see the runway or approach lights clearly, even after penetrating the level of the reported obscuration ceiling. The difference in the two ceilings is illustrated in figure 14-2.

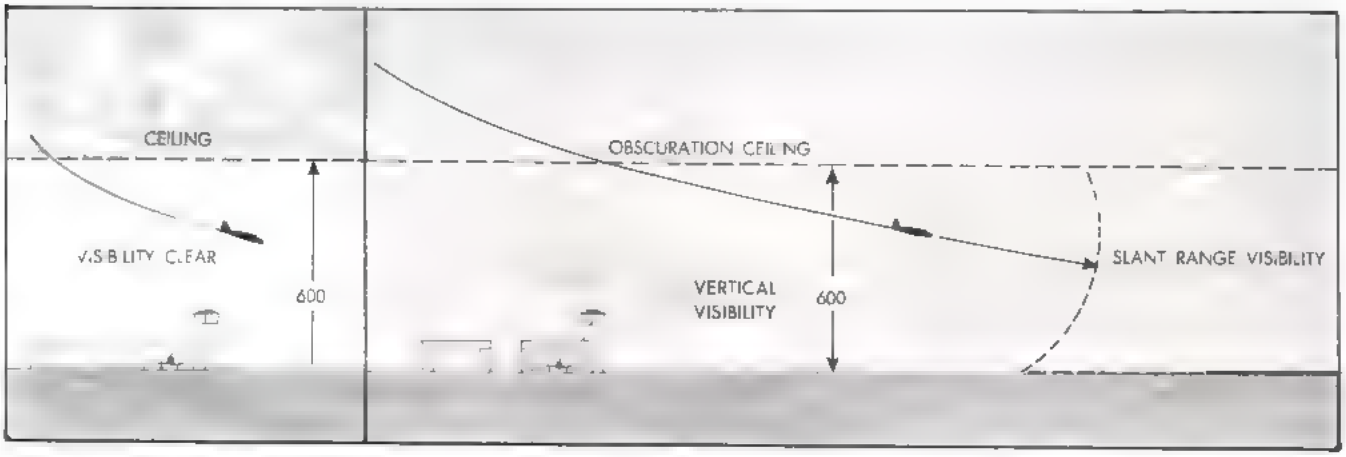


Figure 14-2. Visibility With Cloud Or Obscured Ceiling Condition.

Partly Obscured Sky

If clouds or part of the sky can be seen above the obscuring phenomenon, the condition is reported as a *partly obscured sky*. A partial obscuration does not define a ceiling. However, a cloud layer above a partial obscuration may constitute a ceiling

Partly obscured skies also present a slant range visibility problem for the aircrew approaching to land but usually to a lesser degree than the total obscuration. From directly overhead, the aircrew may be able to see the runway clearly, whereas the slant range visibility on final approach could be poor.

FOG

Fog is one of the most common and persistent weather hazards encountered in aviation, and it is the most frequent cause of prevailing visibilities less than three miles. Since fog occurs at the surface, it is primarily a hazard during takeoff and landing. Flight visibility above fog is generally good

Fog is a surface-based cloud which is composed either of water droplets or of ice crystals. Since fog normally forms in air which is very stable, there are few collisions between the droplets or ice crystals, and these particles remain extremely small Therefore, a large number of these suspended particles must be present before visibility is greatly reduced.

Ideal atmospheric conditions for the formation of fog are: small temperature-dew point spread (normally 4°F or less), abundant condensation nuclei, light surface wind, and some cooling process to start condensation. Consequently, fog is prevalent in coastal areas where moisture is abundant and in industrial areas where products of combustion provide a high concentration of water-attracting condensation nuclei. Fog occurrences are more frequent in the colder months, but the season and frequency of occurrence vary from one area to another.

Fog may form by cooling the air to its dew point or by adding moisture to the air near the ground. Names of various fogs are based upon the way they are formed.

Radiation Fog

Radiation fog is a relatively shallow fog which forms as a result of radiational cooling of the ground on clear, calm nights. The ground cools the air in contact with it to the dew point temperature *Ground fog* (figure 14-3) is a form of radiation fog.

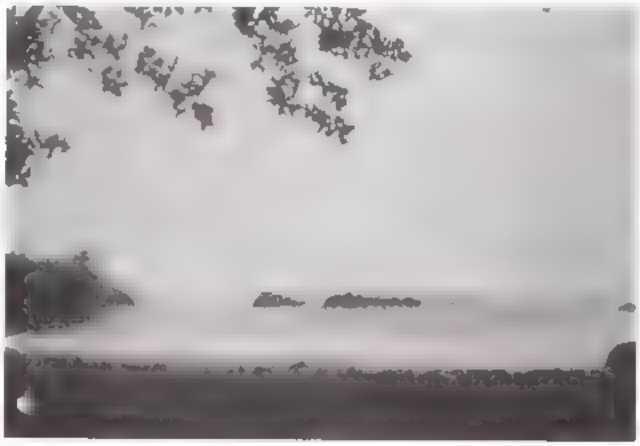


Figure 14-3. Ground Fog.

Radiation fog is restricted to land areas because water areas do not have much daily variation in temperature It forms almost exclusively at night or in the early morning and usually disappears within a few hours after sunrise.

Radiation fog is very shallow when there is no wind flow. Light wind, usually less than 5 knots, produces a slight mixing of the air. This tends to deepen the fog by spreading the cooling through a deeper layer. Stronger winds disperse the fog or mix the air through a still deeper layer with stratus clouds forming at the top of the mixing layer

Advection Fog

Advection fog forms when moist air moves over colder ground or water and is very common along coastal areas. When it occurs over the open sea, it is often called *sea fog*. It can also form as a radiation fog which is then advected by the prevailing wind over surrounding areas. Advection fog deepens as the wind speed increases up to about 15 knots. Winds stronger than 15 knots lift the fog into a layer of low stratus or stratocumulus.

The West Coast of the United States is quite vulnerable to advection fog and stratus. This frequently occurring fog forms offshore, largely as a result of very cold water rising from the ocean depths to the water surface (figure 14-4). The resulting cold air can be carried inland by the wind as stratus or fog.

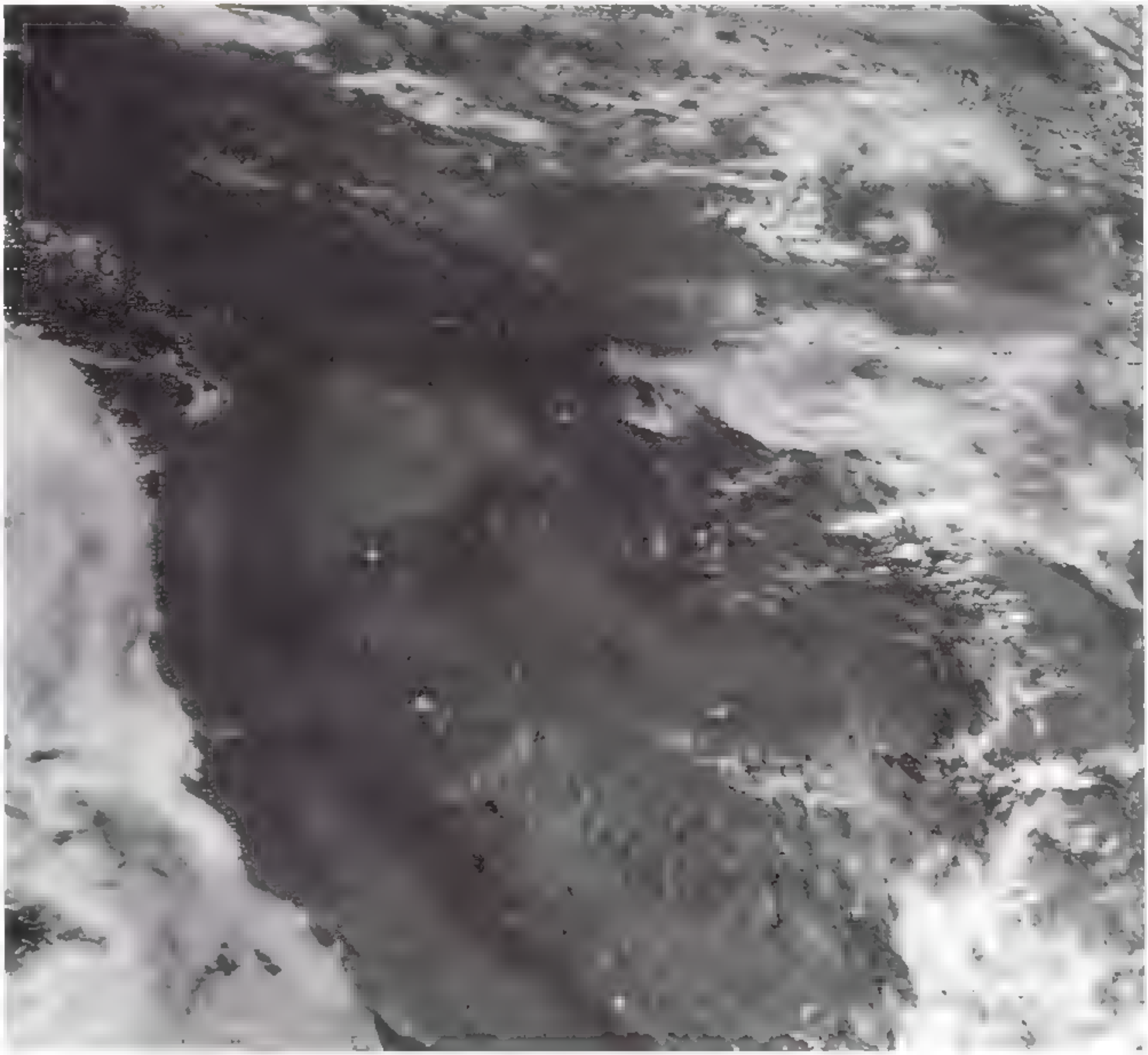


Figure 14-4. Stratus and Fog Off The West Coast Of The United States.

Advection fog over the southeastern United States and along the Gulf Coast results from moist tropical air moving over cold ground. It is, therefore, more frequent in winter than summer.

Water areas in northern latitudes have frequent sea fogs in summer These water areas do not change much in temperature from season to season, but moist, warm air moving north in summer is cooled from below, resulting in fog formation.

Other Types of Fog

When relatively warm rain or drizzle falls through cool air, evaporation from the precipitation saturates the cool air and forms fog (figure 14-5). *Precipitation induced* fog can become quite dense and extend over large areas. It may form rapidly and continue for an extended period of time.

Moisture falling thru cool air

Figure 14-5. Precipitation-Induced Fog.

Upslope fog forms when moist, stable air is cooled as it moves up sloping terrain (figure 14-6). Often it is quite dense and extends to high altitudes.

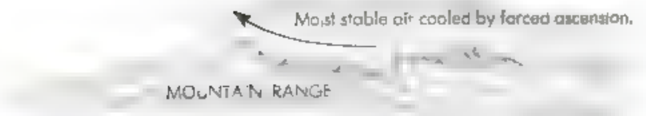


Figure 14-6. Upslope Fog.

Ice fog occurs in cold weather when the temperature is much below freezing and water vapor sublimates directly as ice crystals rather than water droplets Conditions favorable for its formation are the same as for radiation fog except for cold temperatures, usually -20°F (-29 C) or colder.

When the air temperature is approximately -30°F or colder, ice fog frequently forms very rapidly in the exhaust gases of aircraft engines. If there is little or no wind, it is possible for an aircraft to generate enough ice fog during takeoff or landing to cover the runway, thereby halting further aircraft operations. Ice fog may persist for periods which vary from a few minutes to several days

LOW STRATUS CLOUDS

Stratus clouds, like fog, are composed of extremely small water droplets or ice crystals suspended in the air. The distinction from fog is that stratus is a layer above the ground and does not reduce the horizontal visibility at the surface below it.

Stratus and fog can exist together. A cross section of such a condition might appear as a layer of suspended water droplets extending from the ground to some height - perhaps several hundred feet or more - suddenly becoming more dense as the cloud base is entered Because of the reduction in upward visibility, the observer on the ground recognizes the condition as stratus

Both slant range and in flight visibility may approach zero in stratus clouds, depending on the density and depth of the cloud

HAZE AND SMOKE

Haze is a concentration of small salt or dust particles suspended in the air. It occurs in stable air and is usually only a few thousand feet thick, but sometimes may extend as high as 15,000 feet. A haze layer often has a well defined top and good horizontal visibility above. However, downward visibility from above a haze layer is poor, especially on a slant. Visibility in haze varies greatly, depending upon whether the aircrew is facing into or away from the sun. Landing or taking off into the sun is often hazardous if haze is present.

Smoke concentrations form primarily in industrial areas when the air is stable. When smoke and fog occur together, the combination is called *smog* Smog also causes very poor visibility (figure 14-7)

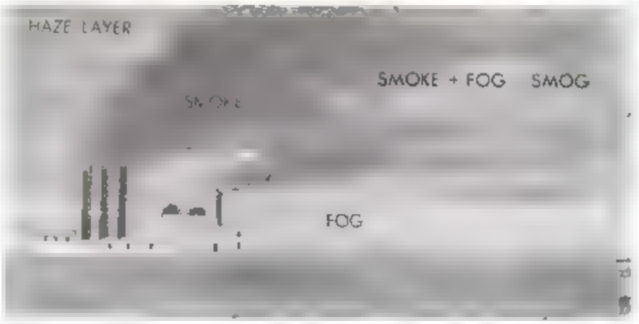


Figure 14-7. Haze and Smog.

OTHER RESTRICTIONS TO VISIBILITY

Blowing dust is observed in areas with loose, dry soil when the air is unstable and the wind is strong (figure 14-8). The wind and vertical currents may spread the dust over wide areas, often lifting it to great heights Very small particles of dust, once airborne, may remain suspended for several days. Both blowing dust and suspended dust reduce surface, in-flight, and slant range visibilities to very low values

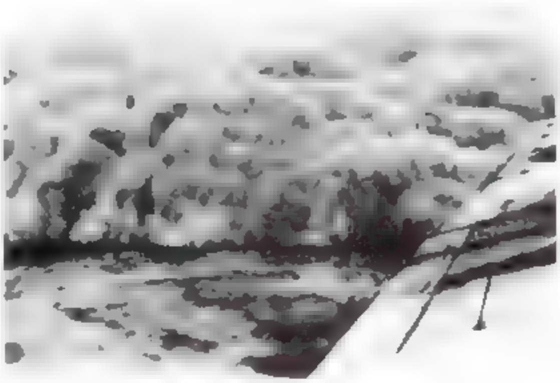


Figure 14-8. Aerial Photograph Of Blowing Dust.

Blowing sand is more local than blowing dust. It occurs in desert regions where loose sand is lifted by the wind and blown about in clouds or sheets. In its extreme form, blowing sand may become a *sandstorm* and restrict visibilities to near zero (figure 14-9)

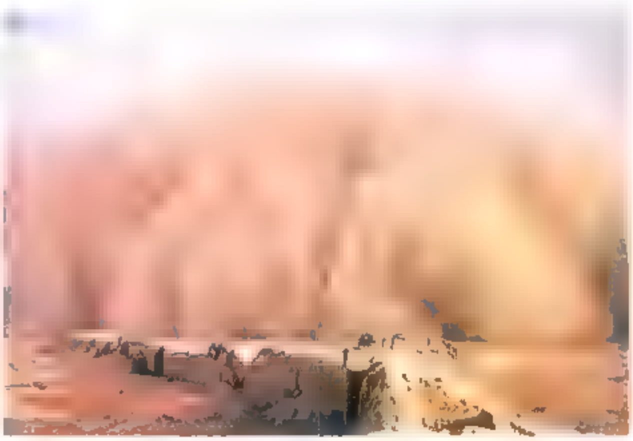


Figure 14-9. Blowing Sand.

Blowing snow can also be troublesome. Visibility at ground level often will be near zero, and the sky may become obscured when the particles are raised to great heights

PRECIPITATION

Rain, drizzle, and snow are the forms of precipitation which most commonly present a ceiling and or a visibility problem

Drizzle and snow usually restrict visibility to a greater degree than rain. Drizzle falls in stable air and, therefore, can be accompanied by fog, haze, or smoke, frequently resulting in poor visibility. Visibility is often reduced to zero during heavy snowfall

Rain seldom reduces surface visibility below one mile, except in brief, heavy showers, but rain does limit cockpit visibility. When rain streams over the aircraft windshield, freezes on it, or fogs over the inside surface, the aircrew's visibility is greatly reduced

CHAPTER 15

TROPICAL WEATHER

The tropics, technically speaking, include that vast region of the earth which lies between the Tropic of Cancer (23½°N latitude) and the Tropic of Capricorn (23½°S latitude) as shown in figure 15-1. However, weather typical of the tropical regions, on occasions, may occur more than 45° of latitude on both sides of the equator. This is especially true for the east coasts of continents. The tropics contain both the wettest and driest regions of the world.

Lower pressure systems are predominant in the tropics, and pressure gradients are ordinarily weak except in tropical cyclones. Since there are no well defined surface pressure systems in this region, other than in these cyclones, local pressure variations frequently are due only to the diurnal effect. However, the main difference between tropical weather and the predominant weather of middle and high latitudes is the relative absence of fronts. Only on rare occasions are fronts strong enough to move into the tropics. Almost all fronts which do reach the tropics produce rain showers, some shift of wind, and a small reduction in temperature.

Most weather in the tropics is a function of the low level and the upper level wind flows. When there is low level convergence of wind flow, along with upper level divergent flow, vertical motion results. This combination in the tropics almost always results in towering cumulus clouds and heavy rain showers.

The typical day-to-day weather which occurs over the tropical oceans differs from weather over tropical continental areas. Along coastal regions and over islands, a combination of these two types (land and ocean) usually results.

OCEANIC TROPICAL WEATHER

Cloud-cover varies from clear to scattered over the tropical oceans outside the equatorial trough. The bases of the clouds are usually about 2,000 feet. Heights of cloud tops vary greatly, with maximum tops around 8,000 feet. Often lines of cumulus align themselves with the wind flow. Visibility is good except in scattered rain showers.

Dew points stay almost constant in the oceanic tropics so the relative humidity is controlled by the temperature. But even the temperature variation is small over the tropical oceans, rarely varying more than 4°F from day to day or from month to month. The freezing level is usually between 15,000 and 16,000 feet throughout the year.

CONTINENTAL TROPICAL WEATHER

The weather over interior continental areas within the tropics is subject to extreme climatic variation. Factors which control the climate are the pressure pattern and

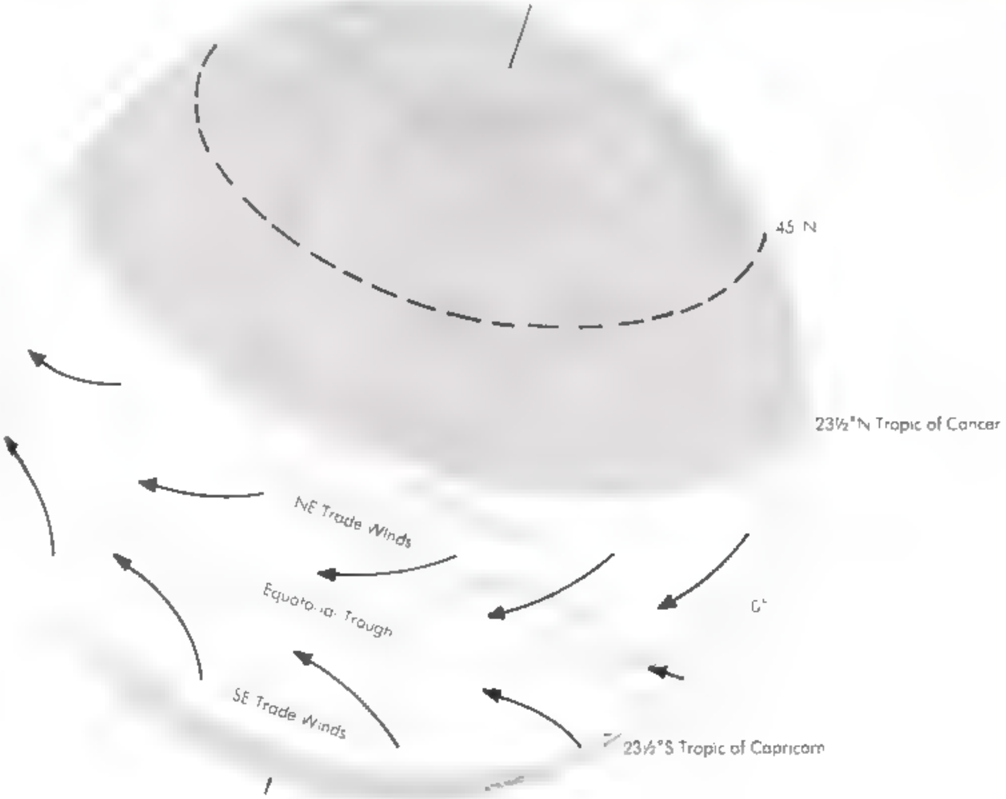


Figure 15-1. The Tropical Zone.

wind flow, orientation, height and extent of coastal mountain ranges, altitude of the continental area, and rate of evaporation from the surrounding ocean surface. Various combinations of these factors produce tropical weather ranging from the hot, humid climate of the lower Congo River, to the arid Libyan Desert, and to the snow-capped mountains of Kenya and South America. Snow is not uncommon on the higher mountain peaks of the Hawaiian Islands.

Arid Tropical Weather

The climate of land areas to the lee of mountain ranges or on high plateaus is characterized by hot, dry, unstable continental air (for example, the desert regions of South America and Africa). The afternoon temperature may be in excess of 100°F in these areas, but the night temperature in desert regions may drop below freezing. Strong convection is present during the day, but low relative humidity at the surface keeps the cumuliform cloud bases above 10,000 feet. Precipitation falling from high-based thunderstorm clouds often evaporates completely before reaching the ground. These "dry" thunderstorms, however, produce gusty winds and may cause severe dust or sand storms. Severe turbulence aloft and restricted ceiling and visibility, accompanied by gusts and squalls near the ground, present hazards to aircrews. An added hazard is aircraft engine damage caused by the ingestion of sand or dust. This may occur with some aircraft even in a calm wind (figure 15-2).

Figure 15-2. C-130 Ingesting Sand During Engine Run-Up.

Humid Tropical Weather

Where no high terrain or mountains are present to obstruct the flow of maritime air onshore, the warm, moist air influences wide continental areas of the tropics. Cloudiness and precipitation are at a maximum over these jungle regions and tropical rain forests.

In humid tropical climates, the daily variation of wind direction and speed determines the daily variations in cloudiness, temperature, and precipitation. Clouds are mostly cumuliform with afternoon cumulonimbus. The average daytime cloud coverage is approximately 60 percent throughout the year, with maximum cloud coverage during the day.

The annual range in temperatures for jungle stations may be less than 2°F, but the daily range is often 30 F or more. When afternoon showers occur, the descending cold air currents may produce nights with temperatures in the 60°F range. These rain showers are very heavy and produce low clouds that may reduce ceiling and visibility to near zero.

ISLAND AND COASTAL TROPICAL WEATHER

Weather conditions are similar along coastal areas and over the various mountainous islands of the tropics. During the day as warm, moist air moves inland and is lifted over the terrain, large cumuliform clouds may develop. While these clouds are common in coastal areas, the lifting of moist air on the windward side of mountainous islands also produces towering cumulus clouds. These clouds frequently may be seen from long distances, indicating the presence of an island ahead.

The islands, especially when mountainous, also have a very interesting effect on rainfall. The almost constant trade winds result in a predominantly onshore wind on one side of an island, while the opposite side has an offshore wind most of the time. These two sides of an island are referred to as the *windward* and *leeward* sides respectively. Precipitation and cloudiness are considerably heavier on the windward side than on the leeward. An example is the island of Kauai, Hawaii where Mt. Waialeale receives the highest average annual rainfall of all rain gages in the world (460 inches), while only 10 miles away, sugar cane plantations must be irrigated.

EQUATORIAL TROUGH

The northeast trade-wind belt of the Northern Hemisphere and the southeast trade winds of the Southern Hemisphere are separated by a broad area of relatively low pressure and light winds. This area of lower pressure is near the equator and is referred to as the *equatorial trough*. The equatorial trough migrates northward during the Northern Hemisphere's summer season and southward during the Southern Hemisphere's summer. Due to the general light wind flow, land and sea breezes become the predominant wind for extended periods along coastal areas and near islands in this belt.

Convergence of the northeast and southeast winds is always present to a degree and usually some amount of unsettled convective weather is found in the trough at all times (figure 15-3). When the zone of convergence intensifies, thunderstorms develop and sometimes produce wind gusts of 40 to 60 knots. Figure 15-4 illustrates the vertical structure of this convergence zone.

TROPICAL WAVES

Numerous waves are found in the low-level, tropical wind flow. Many times these are reflections of an upper-level trough which may or may not be moving. Extensive weather may be associated with these waves, with the level of intensity dependent on the upper-level flow.

The *easterly wave* is a low-level, tropical weather disturbance occurring in the trade-wind belt. Easterly

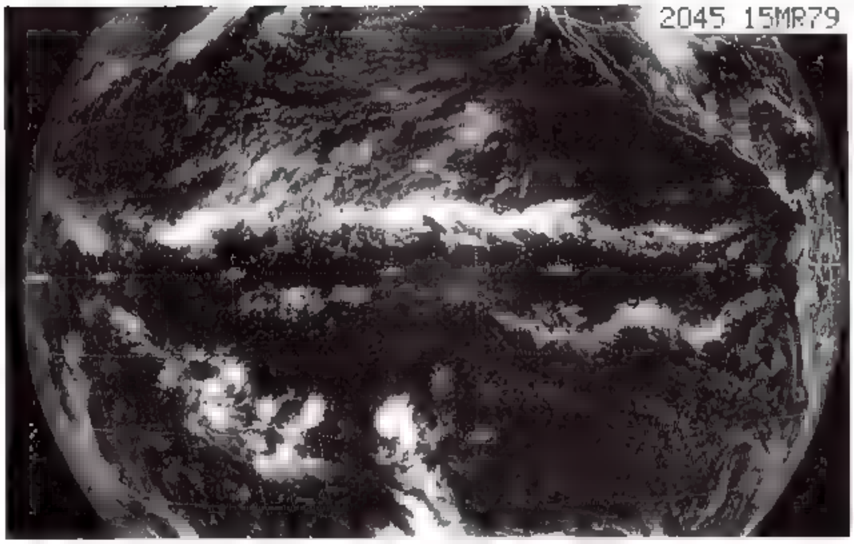


Figure 15-3. Satellite Picture Of Clouds Associated With The Equatorial Trough.

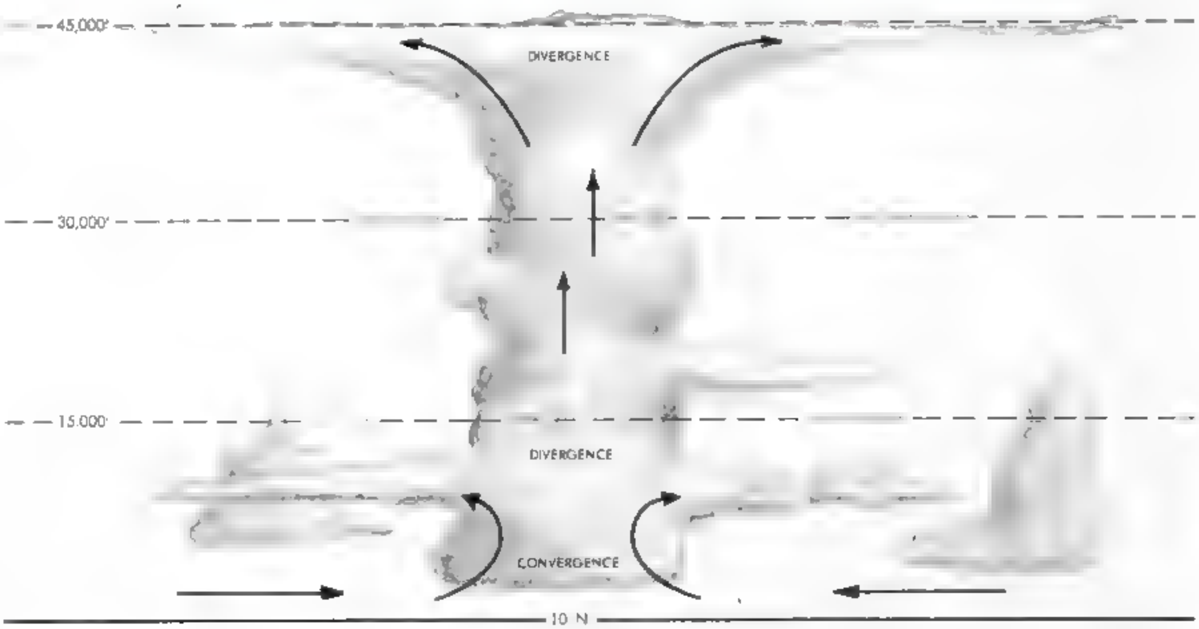


Figure 15-4. Vertical Structure Of Convergence Zone.

waves occurring in the Northern Hemisphere have advance winds somewhat more northerly (NE or NNE) than the usual trade-wind direction as shown in figure 15-5. The wind shifts to the east as the line passes. The typical wave is preceded by very good weather, but followed by extensive cloudiness, low ceilings, rain, and usually thunderstorms. The weather activity is found in roughly a north-south line.

Easterly waves are more numerous and stronger during summer and early fall. Their effects occasionally reach as far north as the Gulf Coast area of the United States. They are commonly observed in the Greater Antilles and Lesser Antilles of the western Atlantic Ocean.

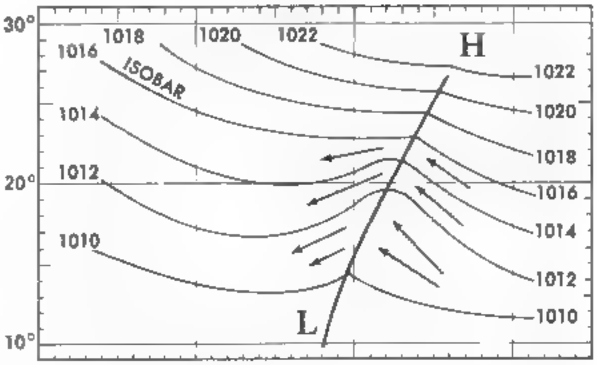


Figure 15-5. Well Developed Easterly Wave.

SHEAR LINES

A line of wind shear, called simply a "shear line," often is found in the tropics as the trailing end of a strong polar front which has moved unusually far to the south. Mixing in the lower latitudes causes density discontinuities across the front to disappear, leaving only a wind shift and a change of wind speed across the diffused front. Convergence and cumuliform activity still may be found along this line of wind shear.

Movement of polar fronts into the tropics sometimes causes the subtropical high to split into two cells, inducing a trough between the cells. More than usual cloudiness and shower activity will be found in this trough. Figure 15-6 illustrates a shear line and an induced trough as they might appear on the surface weather chart.

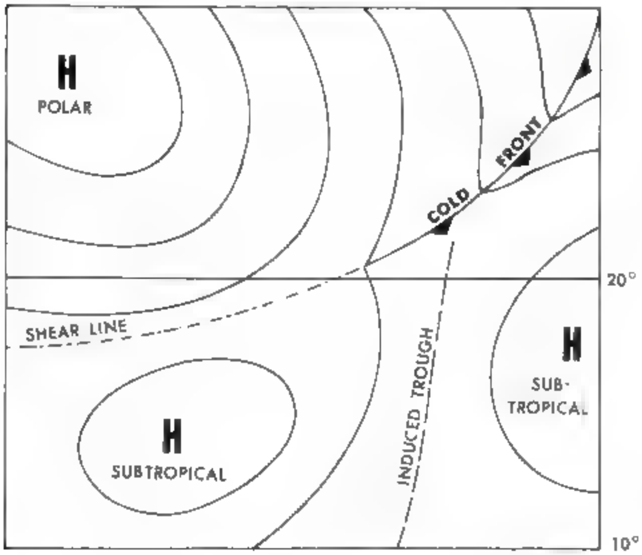


Figure 15-6. Shear Line Resulting From Polar Front Invasion.

THE UPPER TROPOSPHERIC TROUGH

At altitudes above 20,000 feet, upper tropospheric troughs frequently exist in the tropics. Extensive middle and high cloudiness usually is found east of the trough line. These troughs and lows aloft have a considerable effect on the amount of rainfall in the tropics, especially over land areas where mountains lift air to saturation. These low pressure areas aloft contribute significantly to that 460 inches of annual rainfall Mt. Waialeale receives.

MONSOON

The word monsoon does not mean rain. A monsoon is a seasonal shift in the surface wind. More technically this shift must be the result of a reverse from one persistent circulation system to another. This type of regime is found from Central Africa across South Asia and the Indian Ocean to Southeast Asia (figure 15-7). There is no simple correlation between the wind direction and rainfall. For instance in Southeast Asia during the northeast monsoon, some sectors are wet and others are very dry. Generally, the summer monsoon season is characterized by unsettled, showery weather, whereas the winter monsoon has more stable-type weather with stratified clouds (figure 15-8).

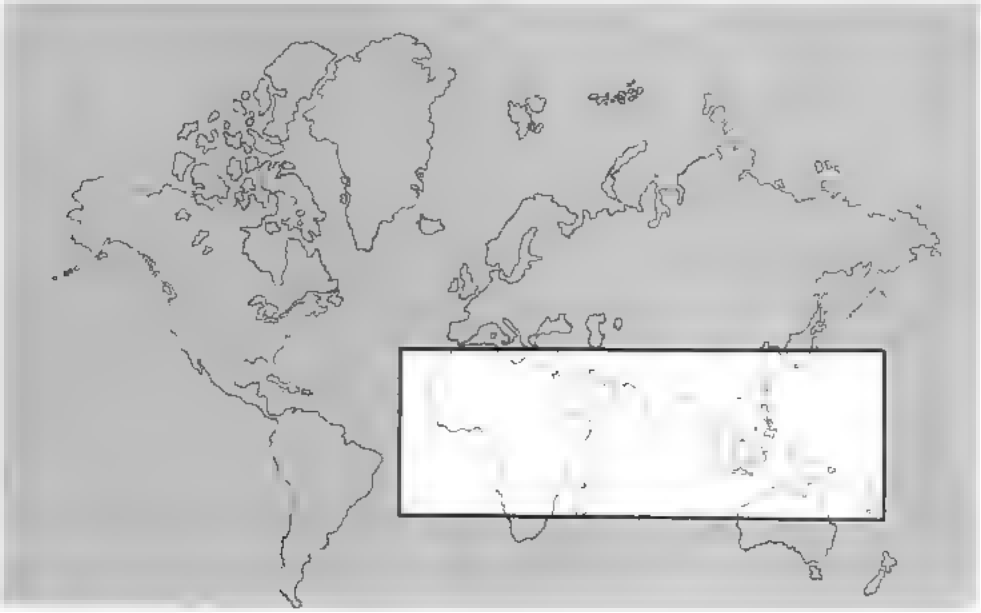


Figure 15-7. General Monsoon Region.

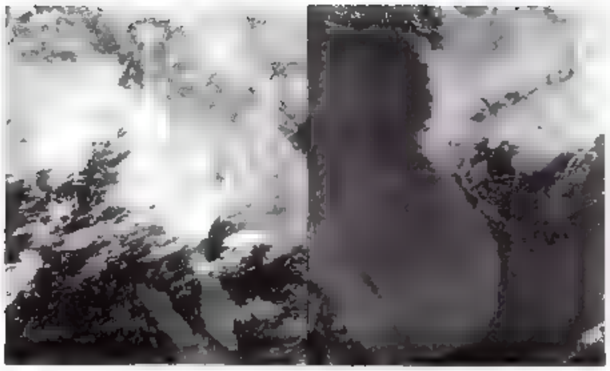


Figure 15-8. Monsoon Flow (Summer And Winter) Over Southeast Asia.

TROPICAL CYCLONES

Tropical cyclone is a general term for any low that originates over tropical oceans. Many regional names are given to these systems. Most Americans know them as *hurricanes*, and this name is used for strong tropical cyclones in the Atlantic and Pacific Oceans, except in the Western Pacific, where they are called *typhoons*. Near Australia, strong tropical lows are called *willy, willy's*, and in the Indian Ocean they are called *cyclones*.

Birthplaces

Tropical cyclones which affect the United States originate over the warm tropical waters of the Atlantic Ocean, the Caribbean Sea, the Gulf of Mexico, the coasts of Central America and Mexico, and the eastern part of the North Pacific Ocean. Figure 15-9 indicates the principal regions of the world where tropical cyclones form and their favored direction of movement. Note that most of them are born between 5° and 15° latitude.

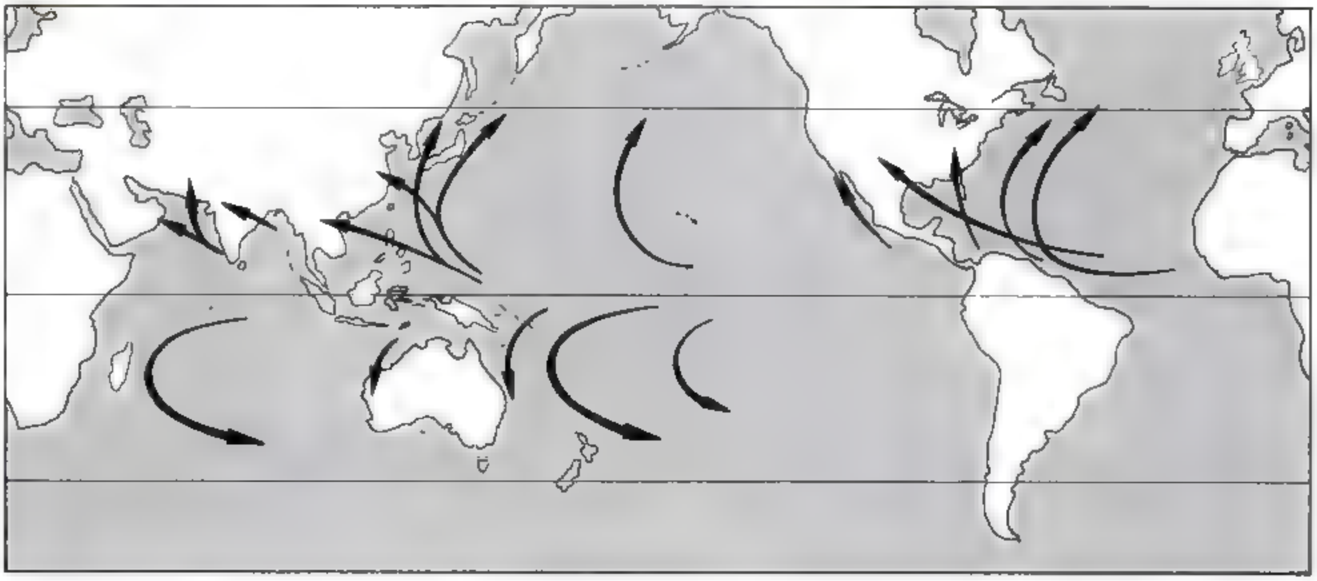


Figure 15-9. Principal Regions Of Tropical Cyclone Formation And Favored Direction Of Movement.

Development

Many tropical cyclones develop in the equatorial trough. In the formative stage the system is called a *tropical depression*. Sustained wind speeds associated with the depression are, by definition, 33 knots or less. By far the majority of tropical cyclones never grow beyond a depression, but on occasions they grow to become *tropical storms*, and even less often they become *hurricanes* (typhoons, cyclones, etc.). The tropical cyclone is classified as a *tropical storm* when sustained winds have speeds between 34 and 63 knots. In the mature stage, the system reaches hurricane intensity and is characterized by sustained winds of 64 knots or stronger. Sustained winds associated with hurricanes are frequently in excess of 100 knots near the center. Occasionally, sustained winds exceeding 150 knots, with still higher gusts, may occur in well developed systems.

The season of North Atlantic tropical storms and hurricanes is August, September, and October. They are very rare from December until May.

Movement

The progressive movement of hurricanes while in the tropics averages only 10 to 12 knots. Direction of movement in the Northern Hemisphere is usually westward or northwestward until they reach 25° to 30°N latitude. At roughly this point, they often begin to recurve and move in a north to east direction (figure 15-10). Following recurvature, they usually move with rapidly increasing speed, sometimes faster than 50 knots.

Eye

Each tropical storm or hurricane has a relatively clear area in the center, 12 to 25 miles across, called the *eye* (figure 15-11). The sky in the storm center often is so clear that the sun or stars become visible, and the wind is comparatively calm. Around this eye is an encircling wall of violent hurricane-force winds. When the eye passes over any location, this calm center is preceded by winds of great violence from one direction and is followed by violent winds from the opposite direction.

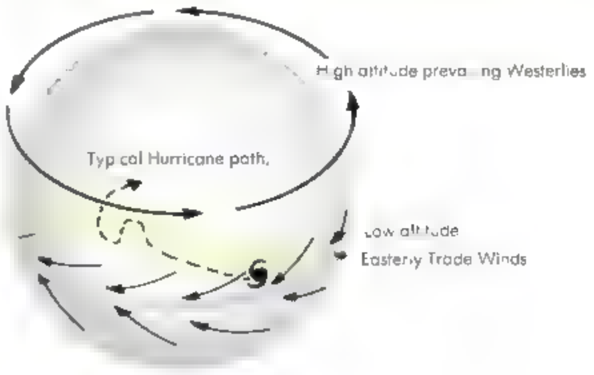


Figure 15-10. Hurricane Movement In Northern Hemisphere.

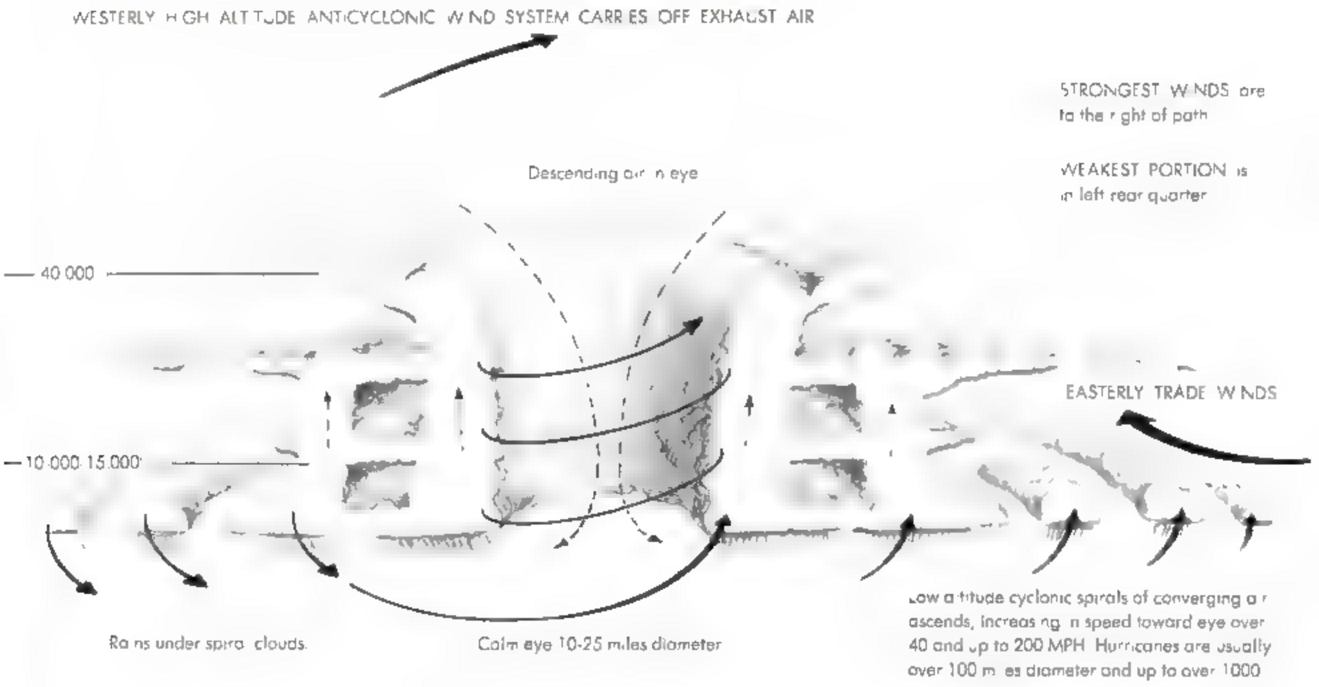

WESTERLY HIGH ALTITUDE ANTICYCLONIC WIND SYSTEM CARRIES OFF EXHAUST AIR
STRONGEST WINDS are to the right of path
WEAKEST PORTION is in left rear quarter
Descending air in eye
40 000
10 000 15 000
EASTERLY TRADE WINDS
Rains under spiral clouds.
Calm eye 10-25 miles diameter
Low altitude cyclonic spirals of converging air ascends, increasing in speed toward eye over 40 and up to 200 MPH Hurricanes are usually over 100 miles diameter and up to over 1000

Figure 15-11. Cross Section Of Hurricane Eye and Spiral Bands.

Rainfall

The rainfall pattern revealed in the radar photograph shown in figure 15-12 is typical of that of a mature hurricane. The characteristic "spiral band" appearance of the rainfall distributed about a hurricane is evident through the white areas in the photograph. Individual convective showers and thunderstorms become aligned in this pattern about the center of the storm.The heaviest rainfall ordinarily is found in the semi-circle to the right of the direction of movement of the hurricane, where accumulations have, on occasions, exceeded 40 inches in a 24-hour period

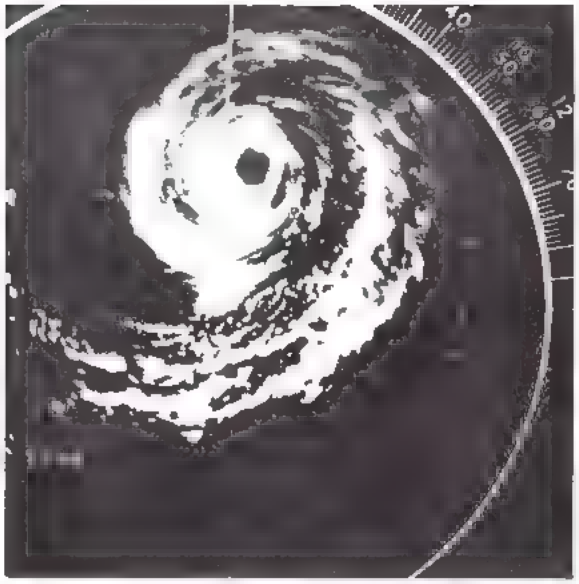


Figure 15-12. Radar Photograph Of Hurricane Showing Spiral Rain Pattern and Eye.

Hurricane Damage

The torrential rainfall accompanying hurricanes often floods interior land regions, while the violent winds bring much destruction. However, the greatest loss of life and property is usually a result of rises in the level of the sea along coastal areas. These abnormally high tides are known as *storm surges* and may be as much as 10 to 15 feet above normal tide. A storm surge which occurs at a time of day when the tide is normally high will cause much more flooding than it would at other times

Hurricanes (including typhoons and cyclones) cause the most widespread destruction of all storms. Some of the larger hurricanes have a diameter of up to about 1,000 miles, with destructive winds over an area as large as 500 miles in diameter.

Decay of Tropical Storms and Hurricanes

Cooler surface temperatures, loss of moisture, and increased surface friction cause a tropical storm or hurricane to decay. When the storm curves toward the north or east in the Northern Hemisphere, it usually begins to lose its tropical characteristics and acquires the characteristics of low pressure systems that are normally found in the middle and high latitudes. The latter type of low pressure system is called *extratropical,* meaning "outside the tropics." Weather reconnaissance aircrews have found the roughest flying weather in storms during the transition period between tropical and extratropical.

Detection and Warning of Tropical Cyclones

The National Weather Service maintains a constant watch for the formation and development of tropical cyclones in the North Atlantic Ocean, Caribbean Sea, Gulf of Mexico, and the North Pacific Ocean to 180°. From 180° westward to the African coast, the Joint Typhoon Warning Center (JTWC) located at Guam is responsible for detection and warning of developing cyclones.

Initial detection may be made by analyzing cloud patterns from weather satellite imagery or by analyzing wind reports from ships at sea. Specially equipped weather reconnaissance aircraft are dispatched on demand to any area where the forecaster suspects a tropical cyclone exists or may be forming. In cases where tropical cyclones are approaching foreign nations, we advise the countries of the existence and location of these storms. Figure 15-13 is a satellite photograph of a hurricane.

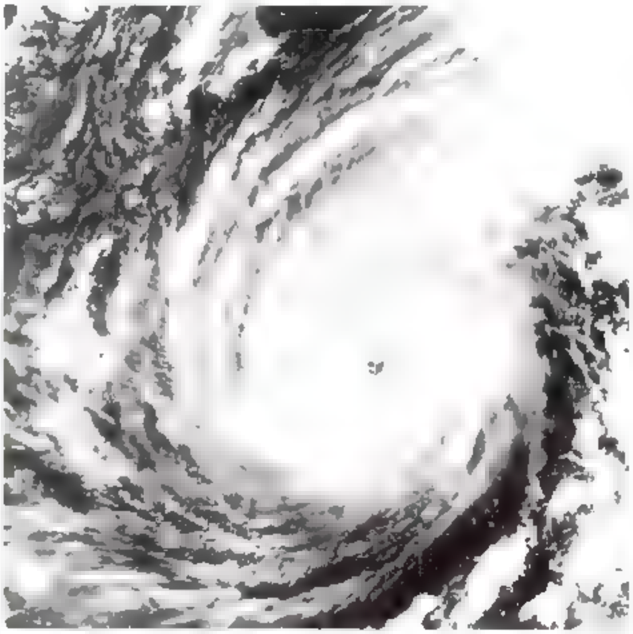


Figure 15-13. Satellite Picture Of A Hurricane.

Tropical Cyclones and the Aircrew

All aircrews, except those specially trained to explore tropical storms and hurricanes, should avoid these dangerous cyclones. The data gathered by weather research aircraft, flying at altitudes of 35,000 to 43,000 feet in the tops of hurricanes, show that severe to occasionally extreme turbulence may be expected in well-developed hurricanes. In the case of lower-flying aircraft, circumnavigation may be accomplished by keeping the storm center to the left of the flight path (for a Northern Hemisphere storm). In this way, the aircraft will experience a tailwind component around the storm.

Winds in a typical hurricane are strongest at low levels and decrease with altitude. However, winds in excess of 100 knots frequently have been measured by research aircraft at 18,000 feet. The change to significantly lighter winds usually occurs at altitudes above 30,000 feet

Some of the most severe turbulence is encountered in the edge of the surrounding wall of the eye. Other areas of turbulence are found within the spiral rain bands. Flight at low levels, 500 to 3,000 feet above the surface, results in exposure to sustained, pounding turbulence due to the surface friction of the fast-moving air.

Critical icing conditions may be encountered in the mid-levels of the storm. At altitudes between 15,000 and 25,000 feet, severe clear icing may render aircraft de-ice and anti-ice equipment ineffective and dramatically decrease aircraft performance.

CHAPTER 16

POLAR WEATHER

Flights in polar regions present special problems for the aircrew. Most of the weather phenomena of special significance occurs at low altitudes or at the surface. Terminal weather conditions are serious hazards in polar flight operations. Obstructions to visibility and depth perception make takeoffs and landings difficult. Iced or snow-packed runways make special flight techniques necessary, and mechanical turbulence becomes a problem when low level winds are strong. These and other flight problems will be examined after a discussion of some general polar features.

POLAR PHYSICAL GEOGRAPHY AND CLIMATIC INFLUENCES

The polar regions, strictly speaking, are the areas which lie north of the Arctic Circle (66½°N latitude) and south of the Antarctic Circle (66½°S latitude). Since the weather hazards are similar for both polar regions, we will confine discussion to weather of the arctic region (figure 16-1). We will also include information on Alaskan weather even though much of the state lies south of the Arctic Circle.

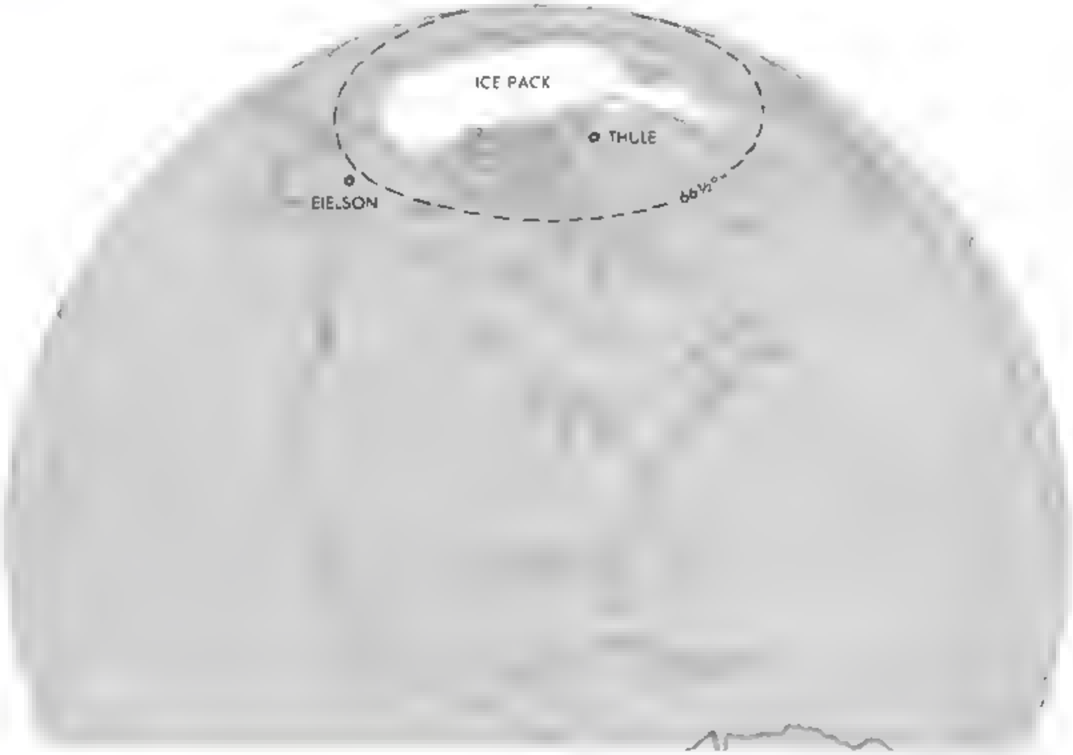


Figure 16-1. Arctic Circle.

The climate of any area is largely determined by the amount of energy it receives from the sun. The heat the area obtains from the sun depends upon (1) the duration of sunlight, (2) the angle of incidence of the sun's rays, (3) the average cloud cover, and (4) land cover.

Figure 16-2 shows that much of the arctic receives little or no direct heat from the sun during the winter. During the prolonged night, there is a continual loss of heat by radiation. This radiative heat loss is a prolonged and continual phenomenon each winter. Notice in figure 16-3 how much more sunlight is received toward the south.

The climate is not completely determined by energy from the sun. The other weather variations are attributed to the distribution of land and water, the physical features of the land, and ocean currents. All these features combine to influence the characteristics of the air-mass source(s) affecting this region.

Water Features

The Arctic Ocean and parts of the North Atlantic and North Pacific Oceans comprise the principal water areas of the arctic. A large portion of the water area encircling the North Pole is covered throughout the year by a deep layer of ice known as the permanent ice pack (figure 16-1). This ice cover becomes larger during the winter months. In summer it is crisscrossed by cracks and open leads.

Even when ice-covered, the water bodies act as temperature moderators since the ice and water below contain more heat than the surrounding cold land. Oceanic and coastal areas have a milder climate during winter than would be expected and a cool climate in summer.

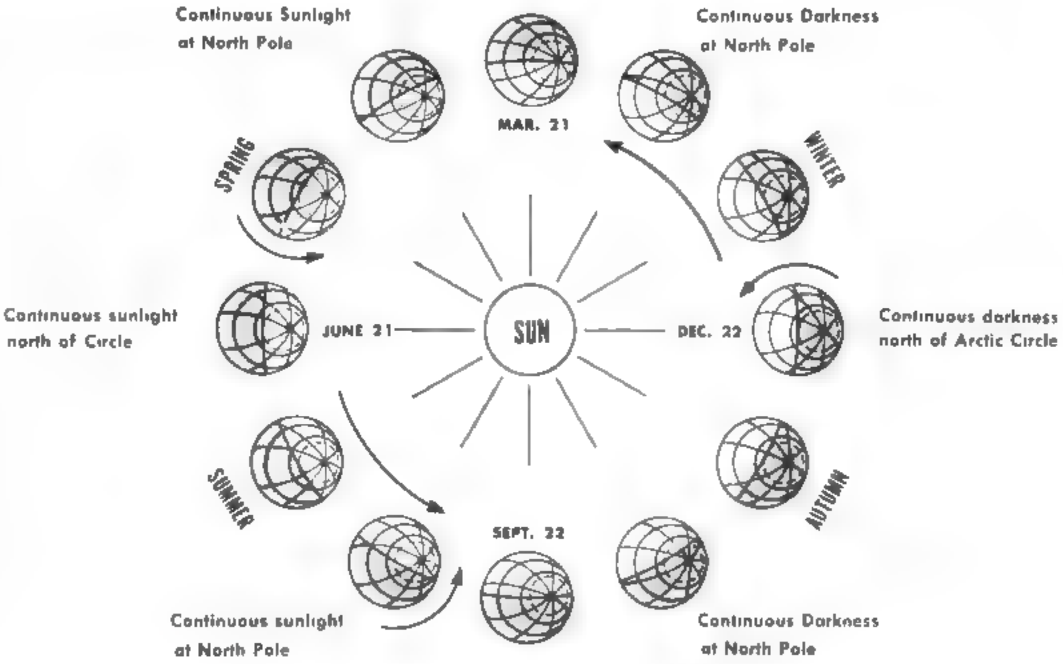

Continuous Sunlight at North Pole
MAR. 21
Continuous Darkness at North Pole
SPRING
WINTER
Continuous sunlight north of Circle
JUNE 21
SUN
DEC. 22
Continuous darkness north of Arctic Circle
SUMMER
AUTUMN
SEPT. 22
Continuous sunlight at North Pole
Continuous Darkness at North Pole

Figure 16-2. Duration And Angle Of Incident Of Sun's Rays Upon Arctic.

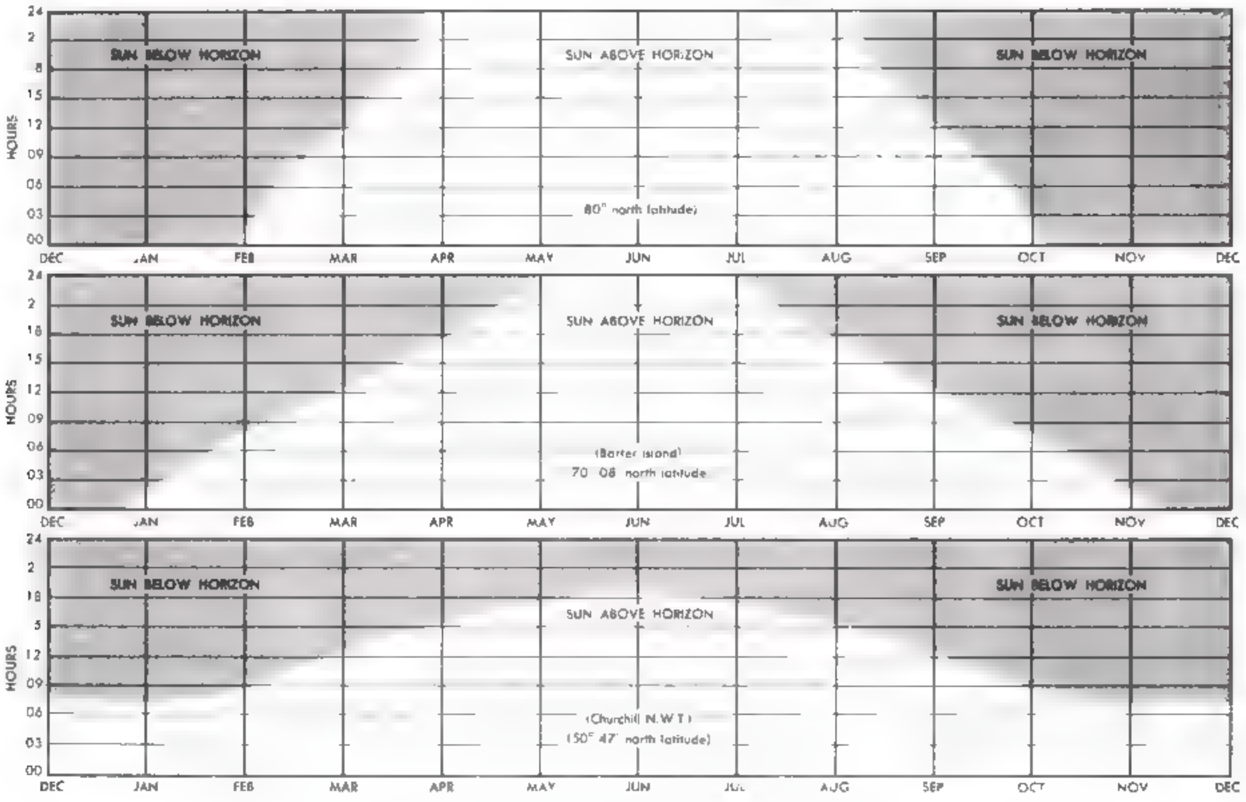


Figure 16-3. Number of Hours Sun Is Above Or Below Horizon (Vertical Lines Represent 21st Day Of Month).

Land Features

Land areas in the arctic (also shown in figure 16-1) include the northern portions of Europe and Asia (Eurasia), the Canadian Archipelago, parts of Alaska, most of Greenland, and the Svalbard Archipelago of Norway.

The arctic mountain ranges of Siberia, North America, and Greenland contribute to the climatic and air-mass characteristics of the regions, since these ranges are effective barriers to the movement of air. During periods of weak wind flow, air is blocked by the mountains and becomes stagnant. The air acquires the temperature and moisture characteristics of the underlying surface and becomes an air-mass source region. Figure 16-4 shows arctic physical features and source regions.

Temperatures

The arctic is usually very cold in winter, but even then some areas are surprisingly warm. Temperatures are usually well below zero in the northern part of the continental interior. During the long hours of darkness, temperatures range from -20°F to -40°F or colder Verkhoyansk in north central Siberia has the record for the Northern Hemisphere of -90°F. Snag in the Yukon Territory of Canada holds the North American record of -81°F. Arctic coastal areas in the winter usually average about 20°F warmer than the interior due to the modifying effect of water and ice.

The interior areas have pleasantly warm summers with many hours of sunshine each day. Figure 16-5 shows the average number of days during each year when temperatures are above freezing. These interior temperatures sometimes rise to the high 70s or 80s and occasionally even into the 90s. Fort Yukon, located just north of the Arctic Circle, has recorded 100°F; Verkhoyansk has recorded 94°F. Arctic coastal areas have relatively cool, short summers. Temperatures occasionally reach the 60s with freezing temperatures reported during winter months.

Clouds and Precipitation

Cloudiness over the arctic is at a minimum during the winter and at a maximum in summer and fall, although there are many cloudy days in spring. The average number of cloudy days at selected locations for the cold and warm seasons is shown in figure 16-6. Scattered cumulus clouds form over interior regions during warm summer afternoons. Occasionally they grow into thunderstorms. Although tornadoes have been observed near the Arctic Circle, their occurrence is extremely rare.

Precipitation (usually snow) in the arctic is generally light. Annual amounts over the ice pack and along the coastal area are only 3 to 7 inches. The interior is somewhat wetter, with annual amounts of 5 to 15 inches, much of which consists of summer rain.

Winds

Strong winds occur more frequently during the fall and winter, especially along coastal areas of the arctic. Wind speeds greater than 70 knots have been recorded at a number of coastal stations. Along the coast of Greenland, winds in excess of 90 knots are not uncommon during winter months.

Figure 16-4. Arctic Physical Features And Typical Air Mass Source Regions.

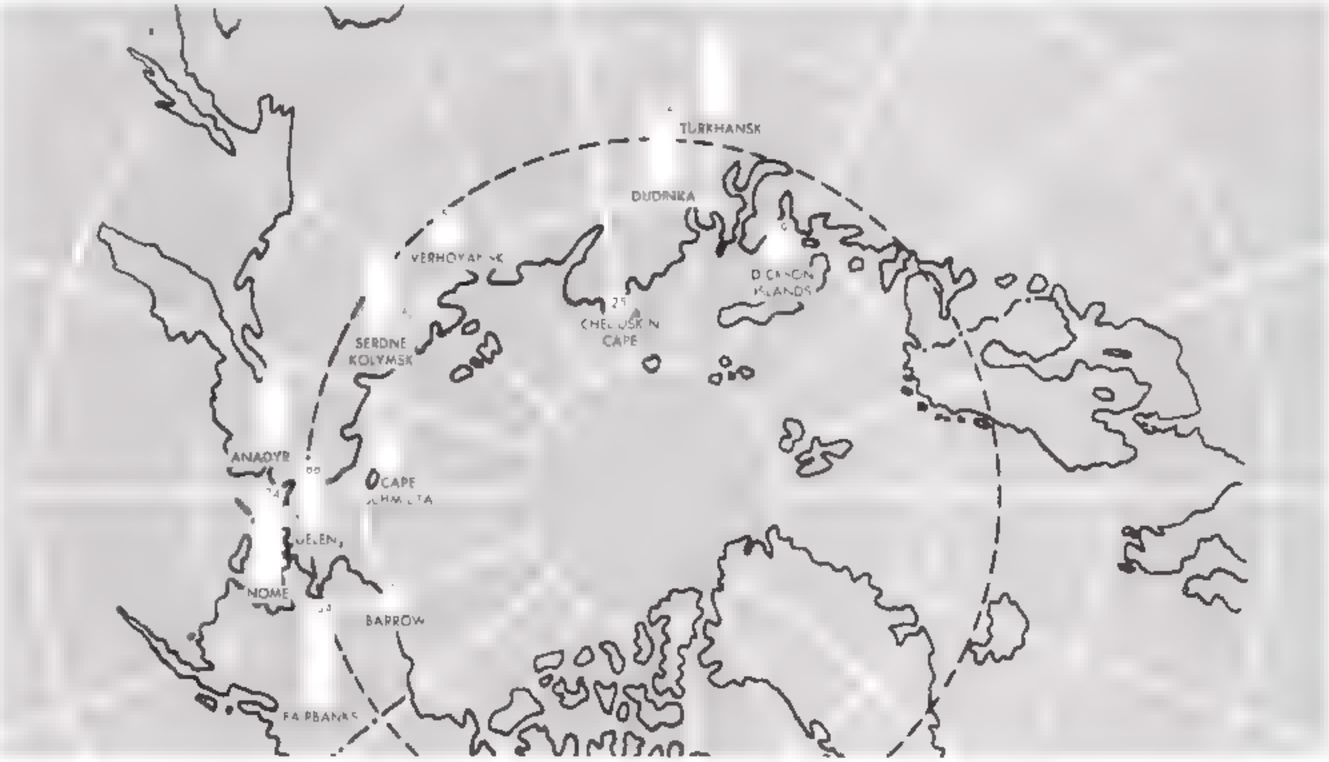


Figure 16-5. Average Number Of Days Each Year With Temperatures Above Freezing.

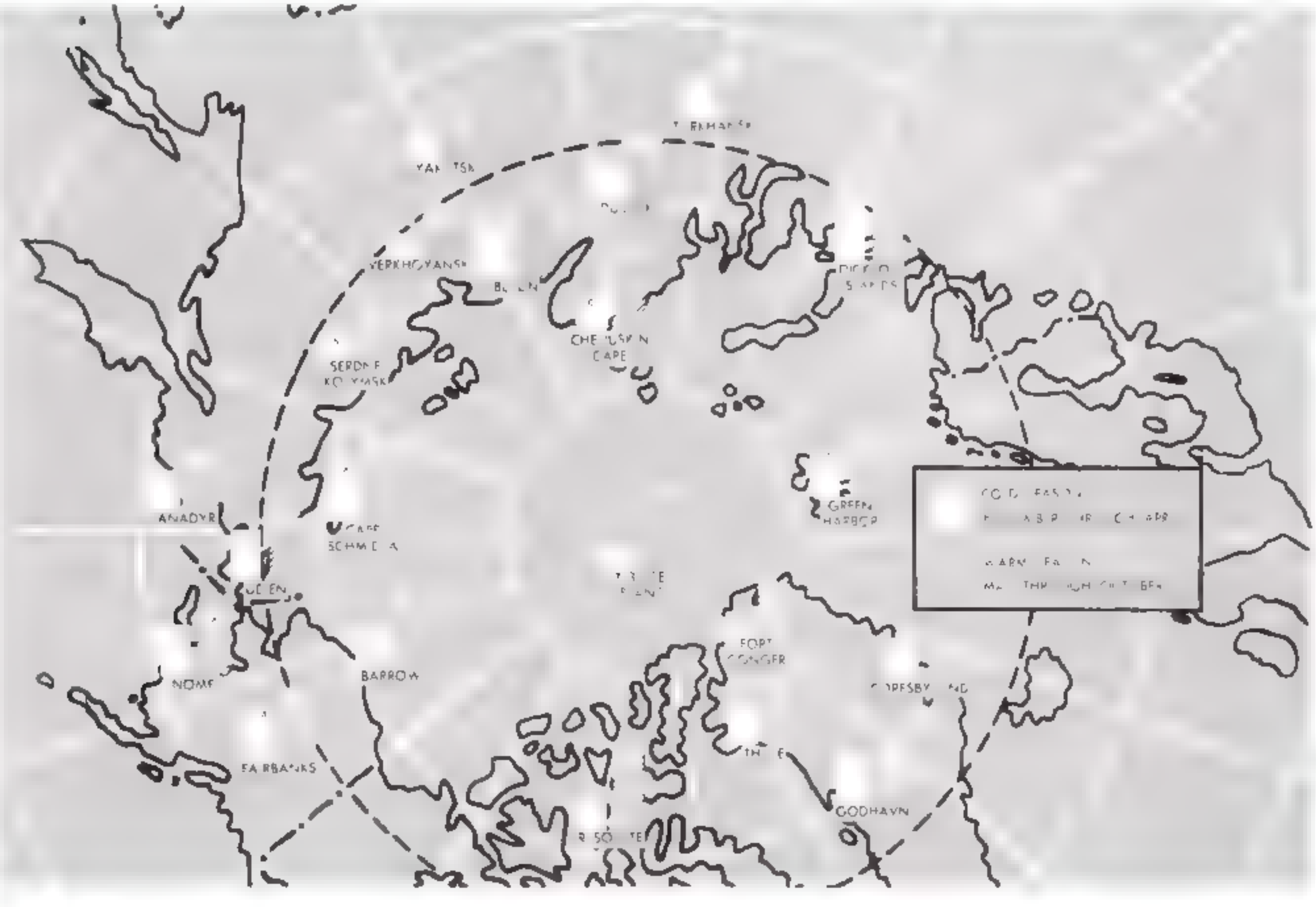
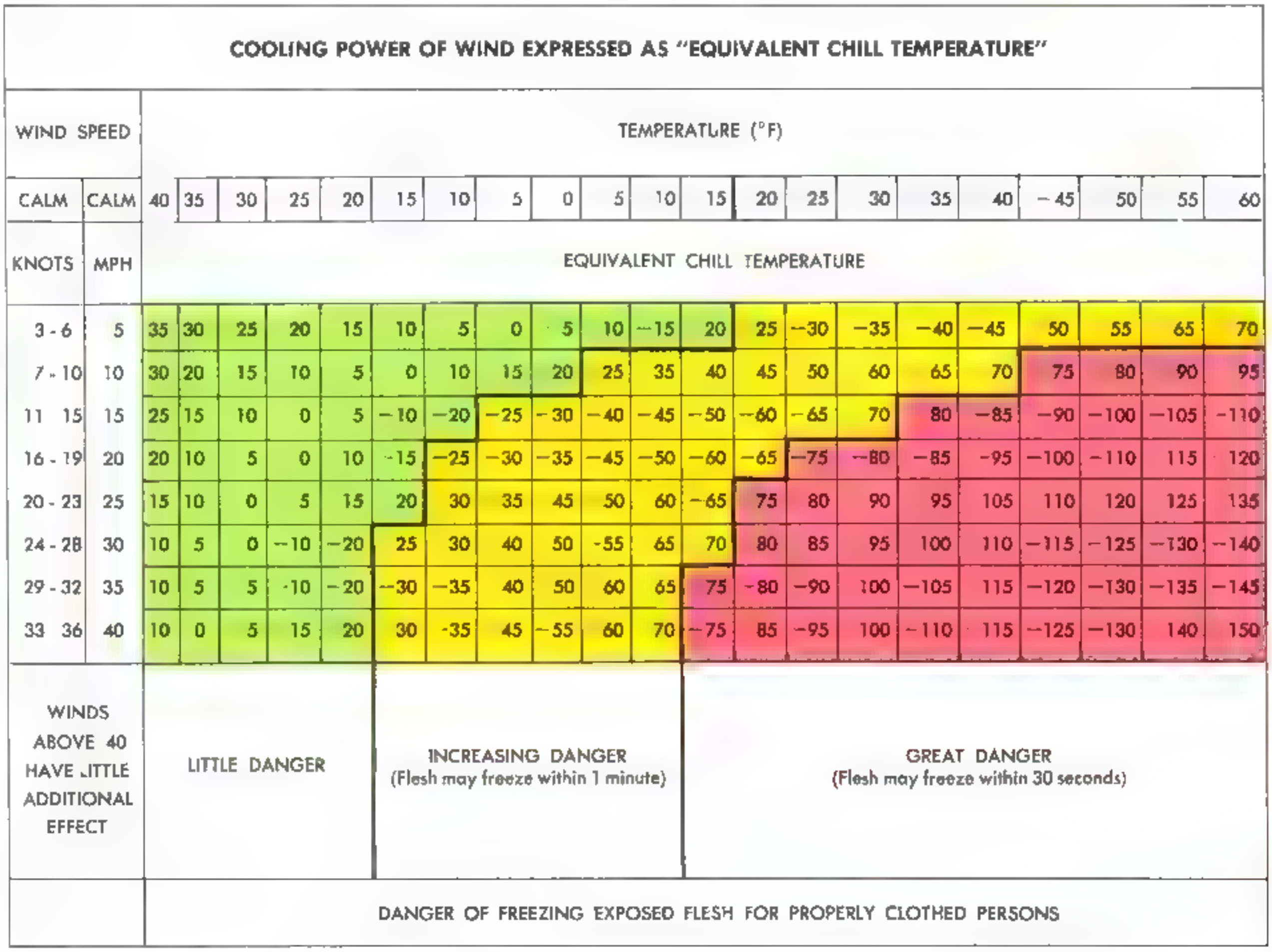


Figure 16-6. Average Number Of Days Per Month On Which Cloudy Conditions Occur.

Strong downslope (fall) winds could prove very hazardous to aircrews. As these cold winds drain from high plateau or mountain areas down to lower elevations, their speed increases abruptly and may exceed 100 knots.

Winds combined with low temperatures make the arctic, especially the coastal areas and the area over the ice pack, very uncomfortable for human activity. The combination produces equivalent chill temperatures that can exceed -100 F. This is computed according to the wind speed at a given free-air temperature and its additional cooling effect on the human body. It is the temperature that would equate the same rate of cooling under calm wind conditions. Figure 16-7 is a chart used in computing equivalent chill factors.



COOLING POWER OF WIND EXPRESSED AS "EQUIVALENT CHILL TEMPERATURE"																						
WIND SPEED		TEMPERATURE (°F)																				
CALM	CALM	40	35	30	25	20	15	10	5	0	5	10	15	20	25	30	35	40	− 45	50	55	60
KNOTS	MPH	EQUIVALENT CHILL TEMPERATURE																				
3 - 6	5	35	30	25	20	15	10	5	0	5	10	−15	20	25	−30	−35	−40	−45	50	55	65	70
7 - 10	10	30	20	15	10	5	0	10	15	20	25	35	40	45	50	60	65	70	75	80	90	95
11 15	15	25	15	10	0	5	− 10	−20	−25	− 30	− 40	− 45	− 50	−60	− 65	70	80	−85	−90	−100	−105	-110
16 - 19	20	20	10	5	0	10	-15	−25	−30	−35	−45	−50	−60	−65	−75	−80	−85	-95	−100	−110	115	120
20 - 23	25	15	10	0	5	15	20	30	35	45	50	60	−65	75	80	90	95	105	110	120	125	135
24 - 28	30	10	5	0	−10	−20	25	30	40	50	-55	65	70	80	85	95	100	110	−115	−125	−130	−140
29 - 32	35	10	5	5	-10	− 20	−30	−35	40	50	60	65	75	-80	−90	100	−105	115	−120	−130	−135	−145
33 36	40	10	0	5	15	20	30	-35	45	−55	60	70	−75	85	−95	100	− 110	115	−125	−130	140	150
WINDS ABOVE 40 HAVE LITTLE ADDITIONAL EFFECT		LITTLE DANGER					INCREASING DANGER (Flesh may freeze within 1 minute)						GREAT DANGER (Flesh may freeze within 30 seconds)									
		DANGER OF FREEZING EXPOSED FLESH FOR PROPERLY CLOTHED PERSONS																				

Figure 16-7. Equivalent Wind Chill Index.

POLAR WEATHER PECULIARITIES

Effects of Temperature Inversions

The rapid increase in temperature with height at low levels over the polar regions during much of the winter causes interesting phenomena. Sound tends to carry great distances under these inversions. Light rays are bent as they pass through the inversion at low angles. This may cause the appearance above the horizon of objects that are normally beyond the horizon. This effect, known as *looming*, is a form of mirage. Mirages which distort the apparent shape of the sun, moon, and other objects are common with these inversions.

Aurora

In theory, certain energy particles from the sun strike the earth's magnetic field and are carried along the lines of force where they tend to lower and converge near the geomagnetic poles. The energy particles then pass through rarefied gases of the outer atmosphere, illuminating them in much the same way as an electrical charge illuminates neon gas in neon signs.

More commonly known as the *northern lights*, the *aurora borealis* (figure 16-8) has its counterpart in the antarctic, where it is termed the *aurora australis* or *southern lights*. While the northern lights occur in the arctic region, they take place at high altitudes above the earth's surface and have been observed as far south as Florida. Displays of aurora vary from a faint glow to an illumination of the earth's surface equal to that of a full moon. The lights frequently change shape and form. The most predominant color is pale green, but yellow, white, red, blue, and violet sometimes are observed

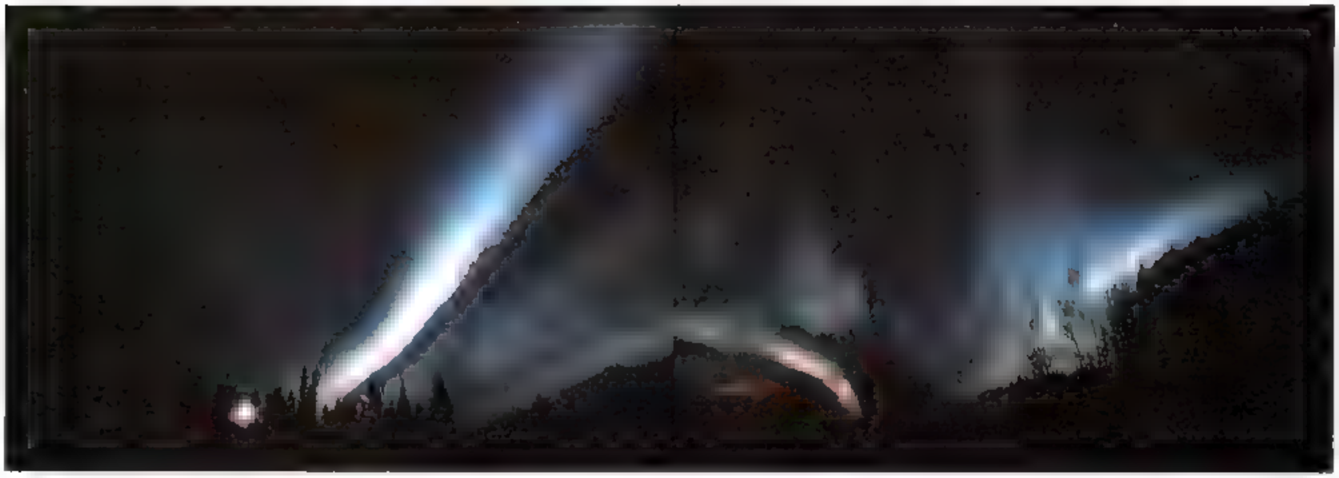


Figure 16-8. Aurora Borealis.

During periods of active aurora, high frequency (HF) radio communications may experience increased noise levels. At times, the noise levels may be severe enough to totally degrade HF radio reception. The interference, which sounds like continuous static, may last from 30 minutes to a few hours.

Light Reflection by Snow-Covered Surfaces

Much more light is reflected by snow-covered surfaces than by the darker surfaces. Snow often reflects arctic sunlight sufficiently to blot out shadows. This markedly decreases the contrast between objects, and it becomes very difficult to distinguish between them. The landscape may merge into a featureless grayish-white field. Dark mountains in the distance may be easily recognized, but a crevasse normally directly in view may be undetected due to lack of contrast.

Illumination from the stars creates visibility far beyond that found elsewhere. Only during periods of heavy overcast skies does the night in the arctic begin to approach the degree of darkness in lower latitudes. There are often long periods of moonlight, with the moon staying above the horizon for several days at a time.

POLAR WEATHER AND AVIATION OPERATIONS

For the most part, fewer and less severe weather hazards exist in the polar regions for aircraft at *flight altitudes* than in other regions. But areas in Greenland compete with the Aleutians for the world's worst weather.

Winter is characterized by frequent storms, but because of the dryness of the air, cloudiness and precipitation are at a minimum. Turbulence is likely to be encountered, especially in mountainous areas.

Whiteout

Whiteout is a visibility-restricting phenomenon that occurs in the polar regions when a uniformly overcast layer of clouds overlies a snow or ice-covered surface. Most whiteouts occur when the cloud deck is relatively low and the sun is at an angle of about 20° above the horizon.

The parallel rays from the sun are broken up and diffused when passing through the cloud layer so that they strike the snow surface from many angles (figure 16-9). This diffused light reflects back and forth countless times between the snow and clouds until all shadows are eliminated. The result is a loss of depth perception. Low-level flight and landings on snow surfaces become dangerous. Several disastrous aircraft crashes have occurred in recent years in which a severe whiteout condition may have been a factor.

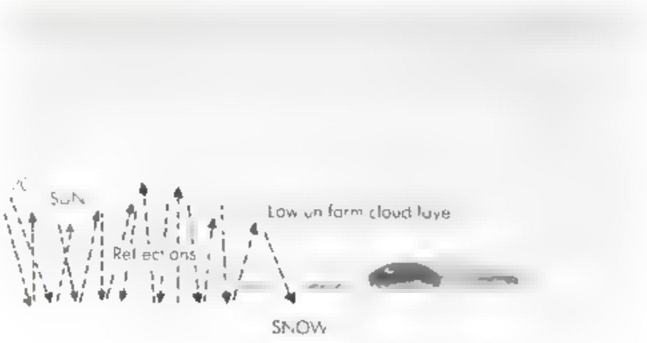


Figure 16-9. Whiteout Condition.

Arctic Haze

Aircrews in flight over polar regions sometimes experience reduced visibility in the horizontal and in looking at surface objects at an angle other than from directly above. Color effects suggest that extremely small ice particles cause this condition. It is also called *arctic* mist when near the ground.

Fog

Fog limits takeoff and landing in the polar regions more than any other visibility restriction.

Water-droplet fog is the main hazard to aircraft operators in coastal areas during the summer. It is a potential source of aircraft icing when the temperature is below freezing.

Ice Fog

Ice fog, a major operational hazard, is common in polar areas in winter. It forms in moist air during extremely cold weather. Ice fog affecting aircraft operations most frequently is produced by the combustion of aircraft fuel in air -20°F (-29°C) and colder.

With supersaturated conditions, routine aircraft engine runup or movement can supply enough exhaust impurities and moisture to cause sublimation. The resulting ice fog may restrict visibilities enough to halt aircraft operations at the airfield for hours.

Blowing and Drifting Snow

Blowing snow is a greater hazard to flying operations in polar regions than in mid-latitudes because the snow is dry and fine and can be picked up easily by light winds (figure 16-10). Winds may raise the snow 1,000 feet off the ground and produce drifts more than 30 feet deep, causing objects such as runway markers to become obscured. Under certain conditions, a frequent and sudden increase in surface winds may cause visibility to drop from unlimited to near zero within a few minutes (figure 16-11). Blowing snow may be deceptive to the inexperienced crew member since the shallowness of the snow layer may permit good vertical visibility at the same time that the horizontal visibility within the layer is very poor.

Temperature Inversion

During the winter, temperatures in polar areas may increase from -60°F at the surface to 0°F only 1500 feet above the ground. Strong temperature inversions, like this, will dramatically decrease the climb performance of an aircraft. Anticipate them and be alert when the weather forecaster briefs the magnitude of the inversion. Then follow procedures listed in your flight manual for cold weather operation.

Altimeter Errors

Strong winds over rough terrain and much-below standard temperatures, which are common in the polar regions, are sometimes responsible for large errors in altimetry. The cause and effect of these errors are discussed in Chapter 4, and understanding them will help the crew member avoid hazards they present. Aircrews should allow for an ample safety margin in selecting flight altitudes over mountainous terrain

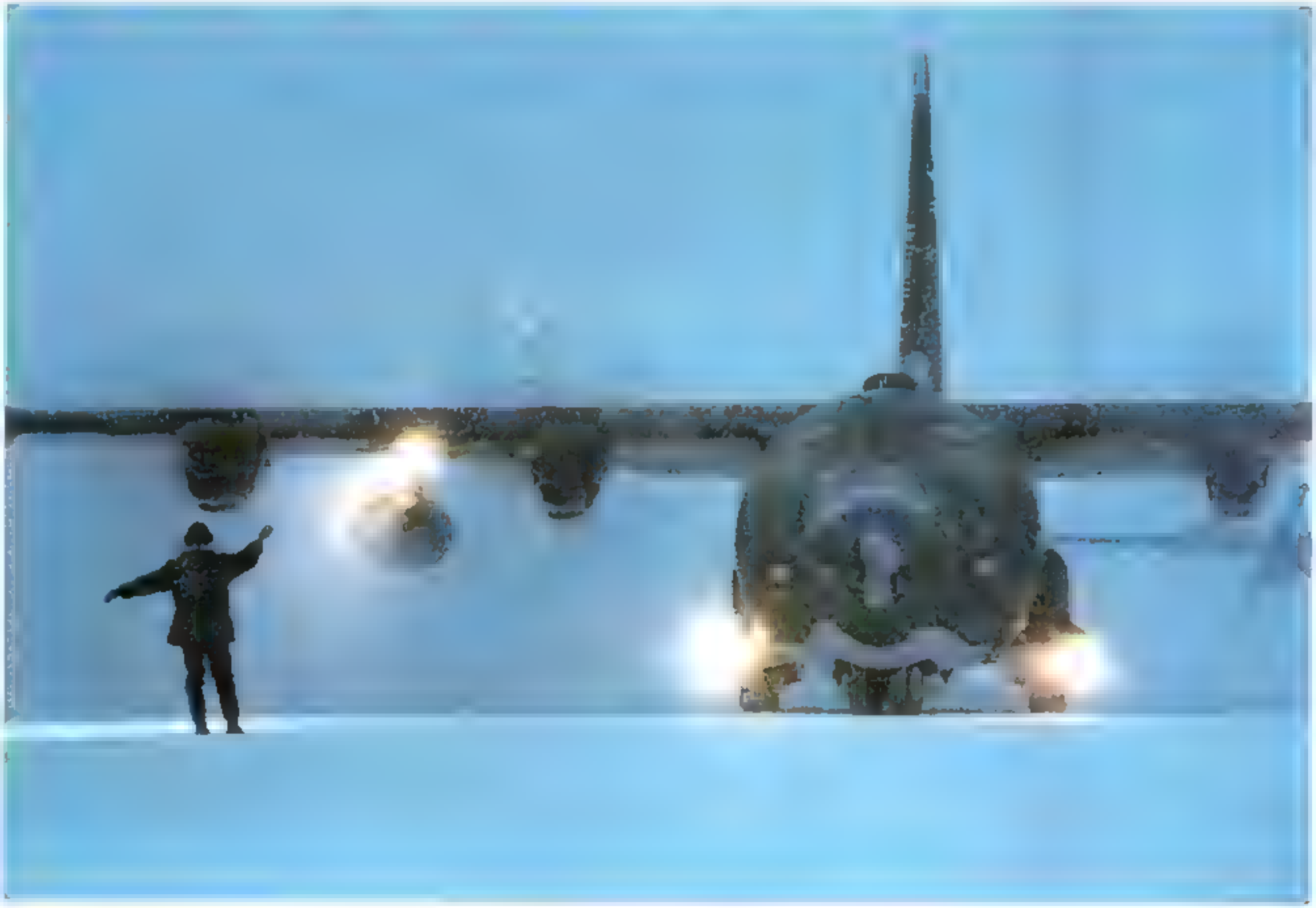


Figure 16-10. Blowing Snow.

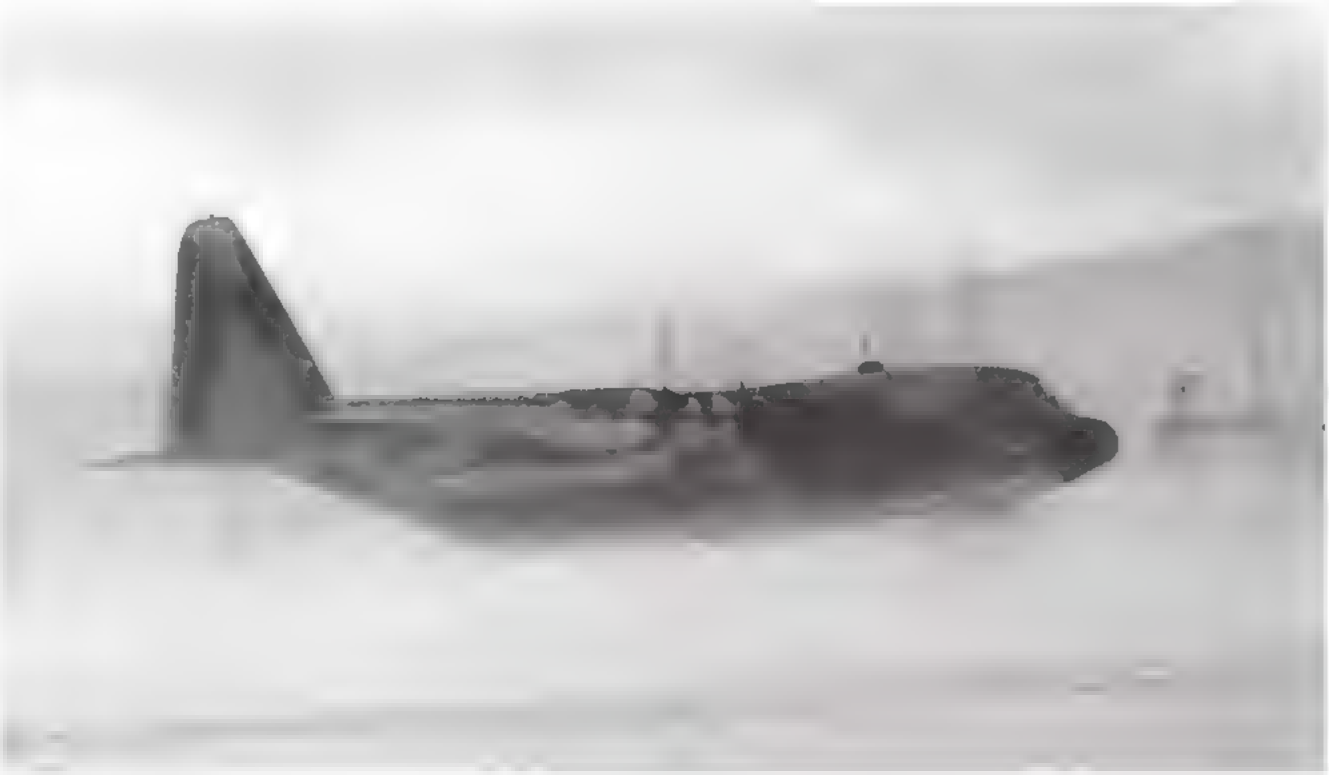


Figure 16-11. Visibility Reduced In Blowing Snow.

BY ORDER OF THE SECRETARY OF THE AIR FORCE

OFFICIAL

LEW ALLEN, JR., General, USAF
Chief of Staff

JAMES L. WYATT, JR., Colonel, USAF
Director of Administration

SUMMARY OF CHANGES

This revision clarifies basic weather information and corrects outdated material. The revision simplifies the explanation of changes of state (Chapter 2), eliminates the discussion of the adiabatic process and temperature lapse rate (Chapter 3), deletes altimetry terminology (Chapter 4), explains the relationship between hurricanes, typhoons, and cyclones (Chapter 5), deletes the discussion of stability types (Chapter 6), enhances the cloud recognition portion of Chapter 7 by including colored photographs and simple descriptions of basic and special cloud types, eliminates the explanation of warm and cold front occlusions, upper fronts, frontogenesis, and frontolysis (Chapter 9), expands the mechanical turbulence section to include turbulence across valleys and canyons (Chapter 10), includes techniques recommended for wake vortex avoidance (Chapter 10), devotes an entire chapter to low-level wind shear (Chapter 11), updates thunderstorm and lightning strike flying procedures and includes discussion of electrostatic discharge (Chapter 13), corrects smog definition and eliminates explanation of fog modification (Chapter 14). The Tropical and Polar Weather section (Part Three) has been completely rewritten to correct outdated information and make it more operationally oriented. Attachment 1 simplifies the explanation of ground-based and airborne radar and includes limitations of each system. This revision also includes a glossary of basic weather terms aircrews can use for easy reference (Attachment 2). Weather codes, charts, and services have been deleted from this volume and are included in AFM 51-12, Volume II.

GROUND-BASED AND AIRBORNE RADAR

Weather radar detects droplets of precipitation size. The droplets may consist of raindrops, hail, snow, cloud droplets, or ice cloud particles. Strength of the radar return (echo) depends primarily on drop size and number of drops The larger the drops and the greater their number, the stronger is the radar echo.

Drop size determines echo intensity to a much greater extent than does drop number. Meteorologists have shown that radar reflectivity is proportional to rainfall rate, and the greatest rainfall rate is in thunderstorms. Therefore, the strongest echoes are associated with thunderstorms, and they mark the areas of greatest hazards. Hailstones are usually covered with a film of water and thus act as huge water droplets giving the strongest returns. Showers show less intense echoes, and gentle rain, drizzle, snow, and clouds give the weakest returns.

Radar information can be valuable both from ground-based radar for preflight planning and from airborne radar for severe weather avoidance.

GROUND-BASED RADAR SYSTEMS

Numerous military weather stations located world-wide are equipped with weather radar. These stations are listed in the appropriate en route supplement. Using the Pilot to Metro Service (PMSV), airborne aircrews can contact AWS forecasters operating storm detection radars. These forecasters are trained to provide weather radar information to en route aircraft as well as those on the ground.

Normally, ground-based military weather radar can display significant precipitation targets within 200 NM of the station and can detect the height of weather returns out to about 120 NM. At stations where the PMSV is collocated with the radar equipment, the forecaster can provide a real-time radar report to airborne crews within radio range

Using the ground-based radar, the weather forecaster can advise the aircrew of the location, movement, horizontal extent, and *radar* tops of *precipitation* (usually not the *visual* tops of the clouds). An estimate of the intensity of the weather returns can also be given, but the forecaster cannot vector the aircraft.

Air traffic control (ATC) radars can also detect weather Although they are primarily designed and used to separate aircraft traffic, they do have limited capability for storm detection. Air traffic control radars generally lack the capability to tilt their antennas so they cannot measure storm tops. These radars also lack calibrated gain reduction, iso-echoing and contouring circuitry, and hence they cannot accurately measure the reflectivity factor of weather returns. Furthermore, normalization factors (applied to radars so echoes nearer the antenna do not appear stronger than strong echoes further from the antenna) are for aircraft targets, *not weather targets*, and they are not standard for all ATC radars. When these radars are used to detect weather echoes, losses in weather echo intensity may occur

Under these circumstances, it is well to remember that the Air Weather Service forecaster's primary job is to assist the aircrew In fact, in the priority of duties, weather service to airborne aircrews is second only to emergency war order requirements. So use the PMSV to learn what is on the weather radar. Then take action on this information, if necessary, by requesting new vectors from air traffic control.

AIRBORNE RADAR SYSTEMS

Airborne weather radar is installed to help aircrews determine the best way to AVOID severe weather echoes. On some occasions, however, it may be necessary for crews to pick their way through an area or line of thunderstorms or showers. This section discusses characteristics and limitations of your radar and techniques to help you avoid severe weather penetration.

Typically, USAF airborne radars have a 3° beam width. A major advantage of this relatively narrow pencil beam is its ability to define the size, shape, and configuration of radar echoes. However, the size of the radar beam cross-section increases significantly at greater detection ranges. Figure A-1 illustrates the beam at 30, 80, and 180 nautical miles.

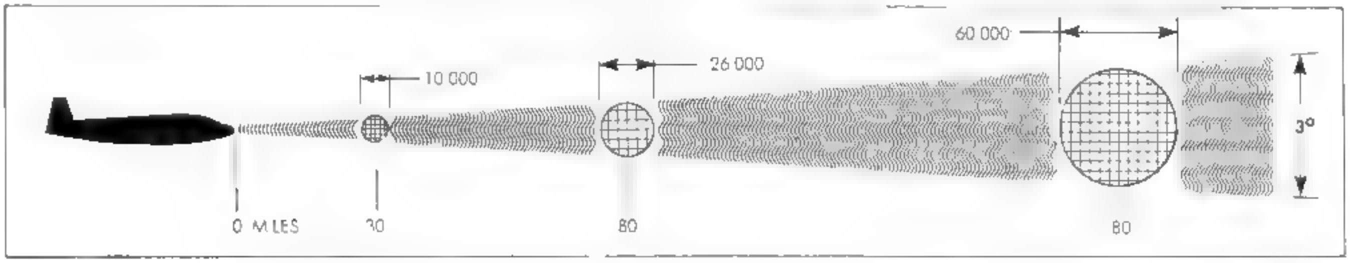


Figure A-1. Radar Beam Cross-Section Illustrating Width at 30, 80 and 180 Nautical Mile Range.

Occasionally, aircrews have reported that a distant thunderstorm appeared as one cell near the edge of the radarscope, and as they approached the storm, it seemed to divide or split in two. Although splitting may occur occasionally, in the majority of cases this is only an *illusion* caused by resolution decreasing with range and the finite width of the radar beam.

At 180 nautical miles the radar beam is more than 10 miles wide. Therefore, if the beam is scanning two cells ahead of the airplane that are closer together than 10 miles, the two separate echoes will appear as one. As you approach, the storms will be scanned by a narrower portion of the beam. At a range of about 80 miles or less, the distance between the cells will become greater than the radar beam width, and you will observe two separate echoes instead of one (figure A-2). Avoid downgrading storm echoes just because they appear to be breaking up as you get closer. By using higher range settings, you will generally have sufficient time to request a clearance from the controlling agency to avoid any storms by the required distance.

The same effect applies in the vertical. Thunderstorms that penetrate the space enclosed by the radar beam will appear as an echo, even though they may still be below your flight altitude (figure A-3). As you approach these storms, they may disappear from the scope, providing they are not still building

Depending on the distance from a particular storm system, it may be possible to observe the variation in height between several cells within the storm complex. Through careful manipulation of the radar antenna tilt control, you may locate small showers as well as large thunderstorms by raising the antenna one degree at a time. As the antenna scan area is raised in successive increments, smaller, low altitude showers will disappear, leaving the larger thunderstorm cells on the radar indicator.

Rapidly intensifying storms develop almost explosively. Growth rates of over 5,000 feet-per-minute have been measured by ground-based radars and confirmed by research aircraft Flying through the top of a building thunderstorm, or just above it, will result in, at best, a strong updraft and associated turbulence. At worst, you may encounter large hail, extreme turbulence, and possible structural damage. To avoid being caught from below by these building storms, keep the radar antenna tilted down about two degrees from the horizontal when in an area of known or suspected developing thunderstorms.

A related problem arises if the aircraft is at low levels or still on the runway. Here ground clutter may mask weather echoes. To avoid this, tilt the antenna upwards until ground clutter appears only at the far edge of the scope. This will allow you to see weather returns and yet not have the antenna tilted upwards so far that the beam is above the echo tops.

When radar energy is transmitted through the atmosphere, it is absorbed and scattered even in clear air. As a result, the strength of the radar energy available for return is gradually weakened. This weakening of the signal is called *attenuation.* Attenuation can be caused by the presence of water droplets, ice particles, clouds, dust, and atmospheric gases

The length of the path that the radar pulse travels through precipitation, clouds, or dust is the key to how much attenuation occurs. In figure A-4, virtually no energy is returned to the radar from the extreme right-hand cell

Attenuation also depends on the water content through which the beam must pass. Over a short path length, attenuation is generally negligible. However, as the path length through the precipitation or cloud increases to 50 NM or more, two-way attenuation increases rapidly. Therefore, do not assume that a lack of echoes beyond a thunderstorm area implies the nonexistence of other, more distant storms Rather, you should always assume that other, more distant thunderstorms exist until proven otherwise. If available, ground-based radar can provide information on the existence of more cells.

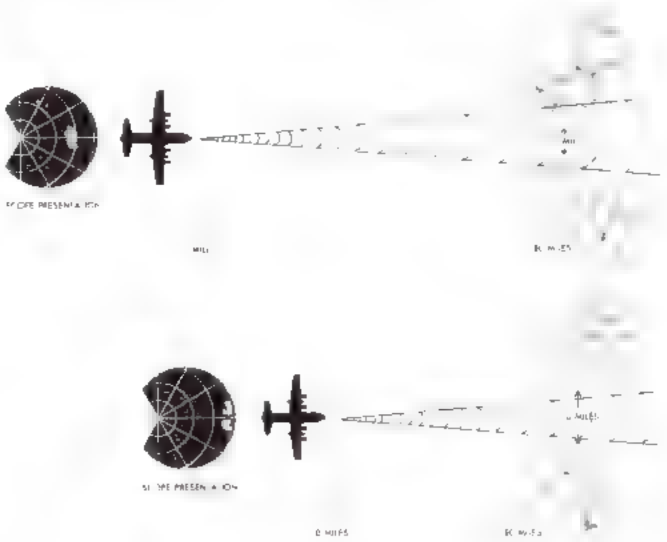


Figure A-2. Storm Echoes Appear To Break Up As Aircraft Gets Closer.

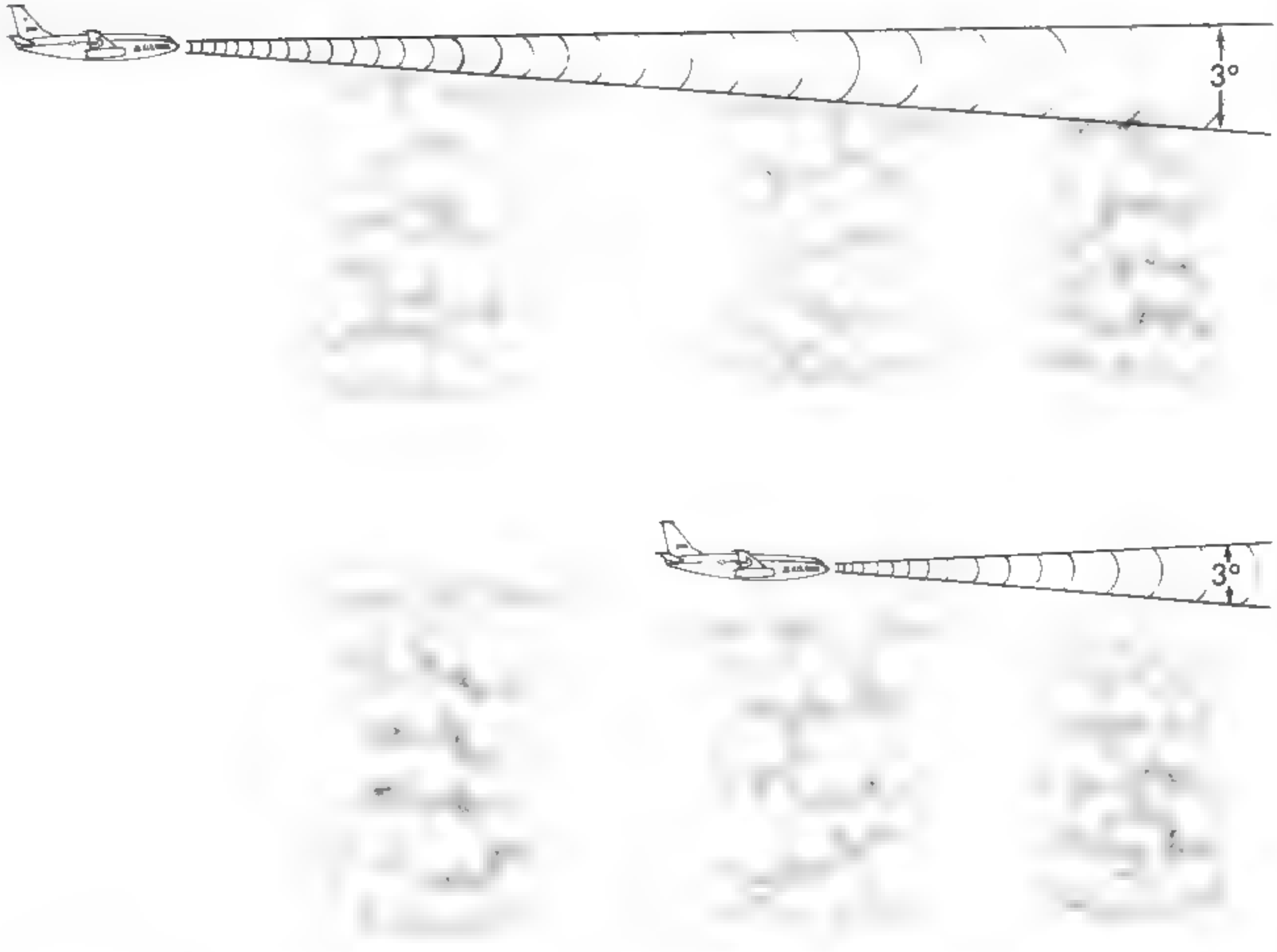


Figure A-3. Thunderstorms Below Flight Level May Disappear As Aircraft Approaches.

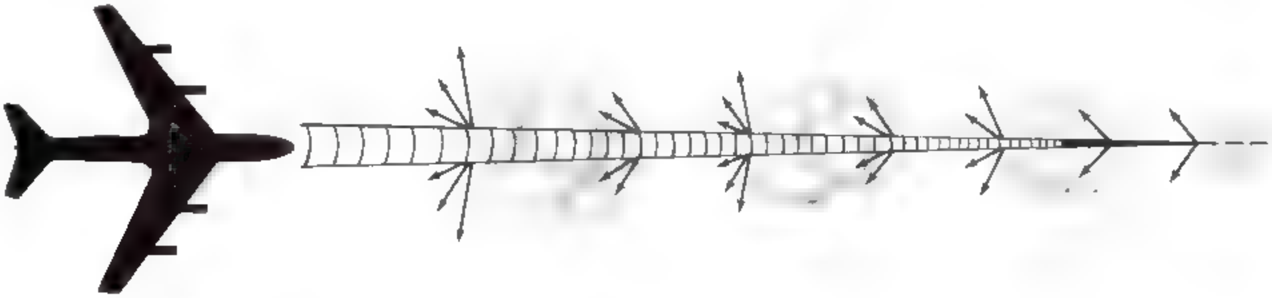


Figure A-4. Radar Energy Attenuation.

Radar Scope Interpretation and Severe Weather Avoidance

Circumnavigating convective storms by observing radar echoes is the best way to avoid hail and turbulence associated with severe weather. On some occasions it is also possible to supplement radar information with your own visual observations of rapidly growing storm cells, hail shafts, and even possible tornado activity, if you are in the clear. At higher cruising altitudes, it is strongly recommended that you avoid all severe weather echoes by at least 20 nautical miles (figure A-5).

Two signal processing features aid in weather echo interrogation. The *iso echo mode* operates on a video cancellation principle. That portion of the echo which exceeds the iso-echo threshold will be cancelled, causing a donut-shaped echo pattern on your scope (figure A 6). This mode is one of your best tools for determining storm strength. Be sure that cancelled areas are not misinterpreted as echo-free areas.

Sensitivity time control (STC) should be used to eliminate apparent intensity variations caused by distance. This feature causes all echoes within approximately 40 nautical miles, depending upon the type of set, to be displayed on your scope in their relative intensity. This precludes interpreting a bright return from a nearby thunderstorm as being more intense than that from a more distant thunderstorm. Both STC and iso-echo modes should be used frequently when observing echoes.

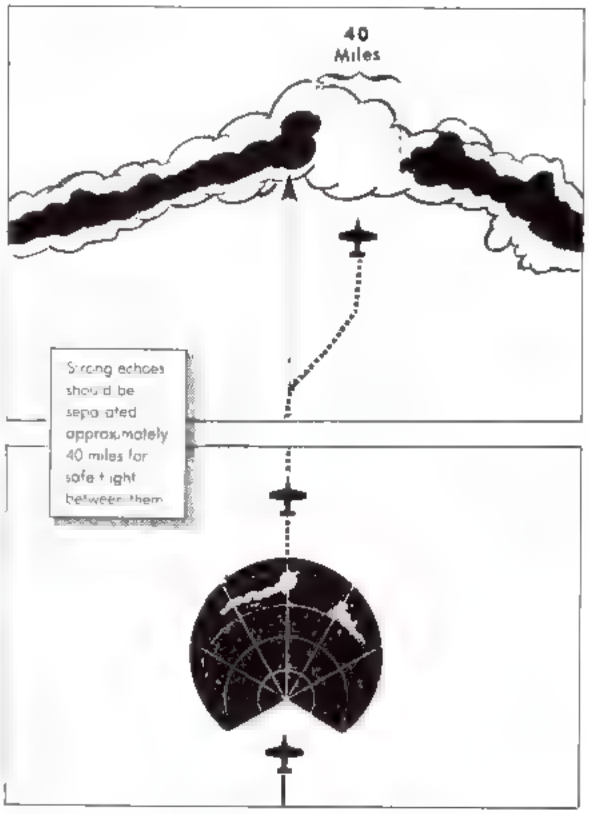

40
Miles
Strong echoes should be separated approximately 40 miles for safe flight between them

Figure A-5. Thunderstorm Avoidance.

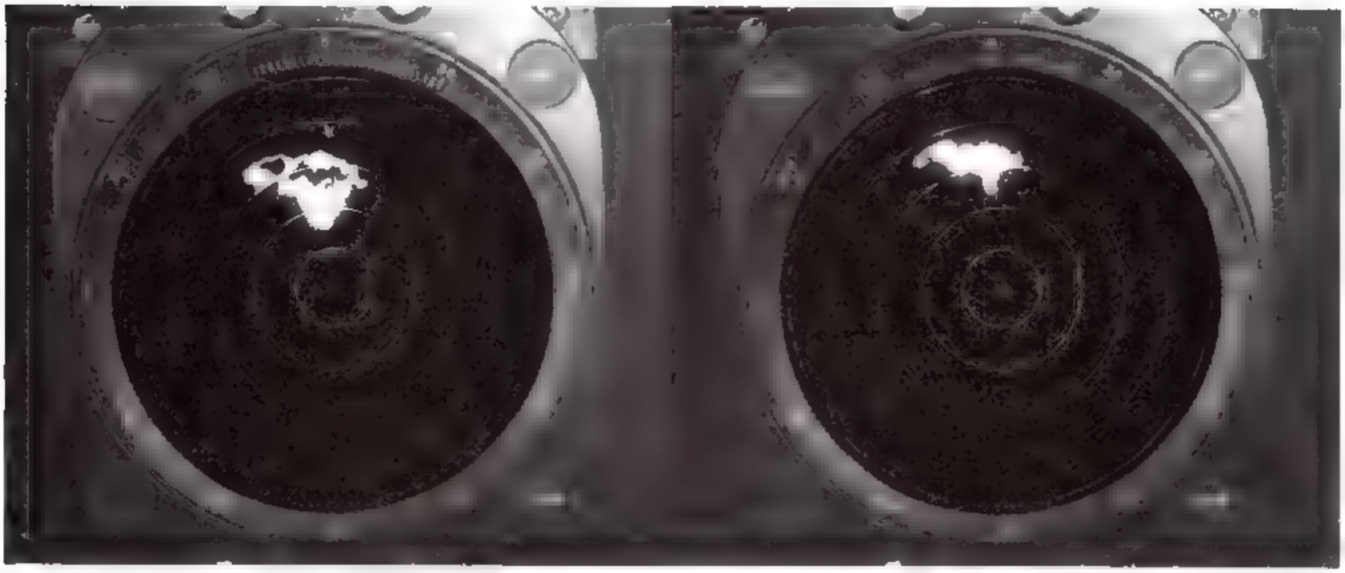


Figure A-6. Airborne Weather Echo With (Left) and Without (Right) Iso-Echo Mode.

Distinct echo shapes and patterns generally associated with severe weather normally will not appear on your scope until you are within 30 to 60 nautical miles of a storm. These features will seldom be visible during high-level flight. However, below 20,000 feet, in terminal areas or on low-level missions, they become highly important. Even at higher altitudes, knowledge of them could be critical for determination of safe avoidance distances.

Figure A-7 depicts four rather characteristic echoes associated with hail, severe turbulence, and possible tornado development. If any of these patterns appear on your scope at distances of less than 60 miles, assume they indicate severe thunderstorms. They are best found by switching iso-echo and STC modes on and off, and comparing the scope presentations

The *scalloped-edged* echo in figure A-7 is a good indication of a rapidly developing storm system. Although difficult to observe, you may notice the outline of the radar echo changing slightly in size and configuration. This indicates good potential for continued storm growth and severe turbulence. Sometimes, one of the unusually shaped appendages may develop into a *finger, hook,* or *V-notch* echo similar to the remaining examples shown in figure A-7.

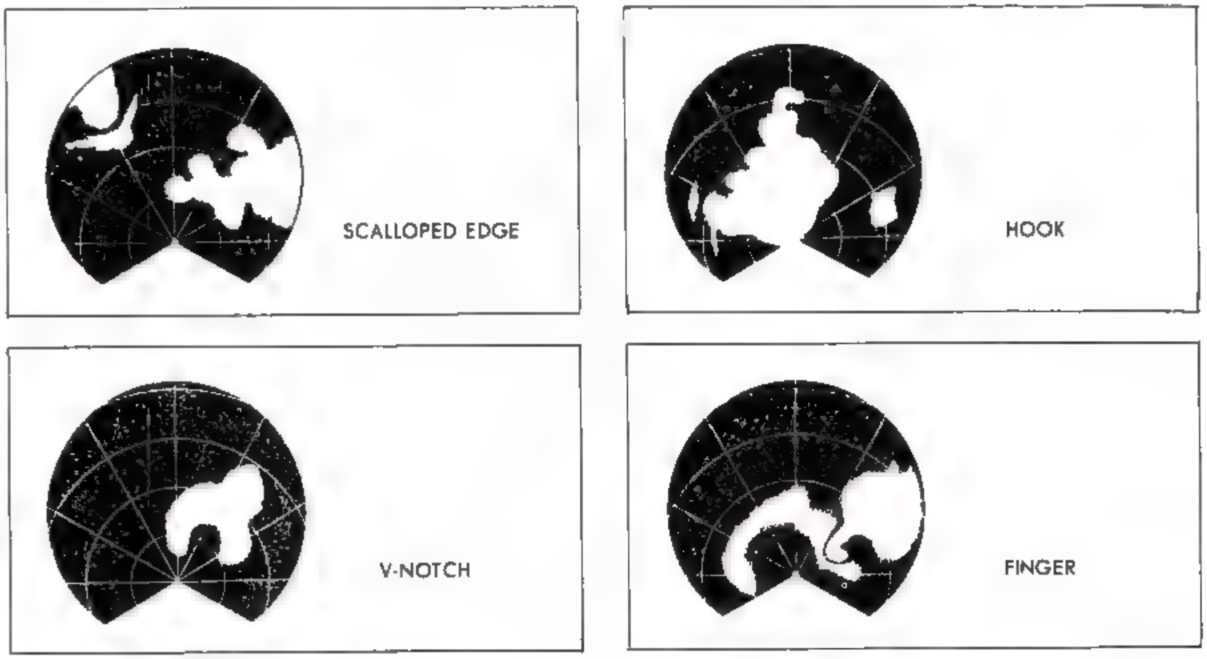


Figure A-7. Radar Echoes Of Severe Storms.

Highly reflective fingers projecting from either the iso-echo core of an echo or the edge of the echo are another pattern associated with severe weather. They are believed to be hail shafts on the fringes of the storm and may change shape rapidly

The hook echo may indicate funnel cloud or tornado development. It is best found by viewing the echo without iso-echo and then with iso-echo. Since funnel clouds are generally observed visually at altitudes below 5,000 feet, tilt the antenna to scan the lower portion of the storm down to ground level.

The V-notch echo may be formed by the merging of two echoes into a single, large echo, forming a "V" at the point of merger. Thunderstorm and tornado development may occur at this point, so aircrews must not fly into this notch believing it to be a narrow gap between two echoes with only a small area of precipitation at the far end.

Flying through layers of overcast cirrus at high altitudes, especially above 25,000 feet, is a rather commonplace event in areas where thunderstorms are numerous. Penetration distance through a thick, overcast, ice crystal cloud-layer with X-band radar will vary, depending on the density of the cloud and the relative intensity of the thunderstorm echoes. It is recommended that you adjust the manual tilt control downward until you pick up ground returns. Then if you can "paint" the ground, you can be sure that the radar is able to penetrate the ice crystal cloud at that antenna tilt angle. Therefore, you should also be able to pick up radar echoes from storm cells at adequate distances to permit you to avoid them in sufficient time

Airborne radar can be an invaluable tool to help aircrews recognize and avoid severe weather encountered in flight. Installation of improved radar with multi-colored displays (figure A-8) will increase the aircrew's ability to distinguish moisture levels in a storm. However, no matter how well radar performs, it is still just a tool. It is your knowledge of severe weather and the expertise with which you operate your radar system that will determine the safety of your flight

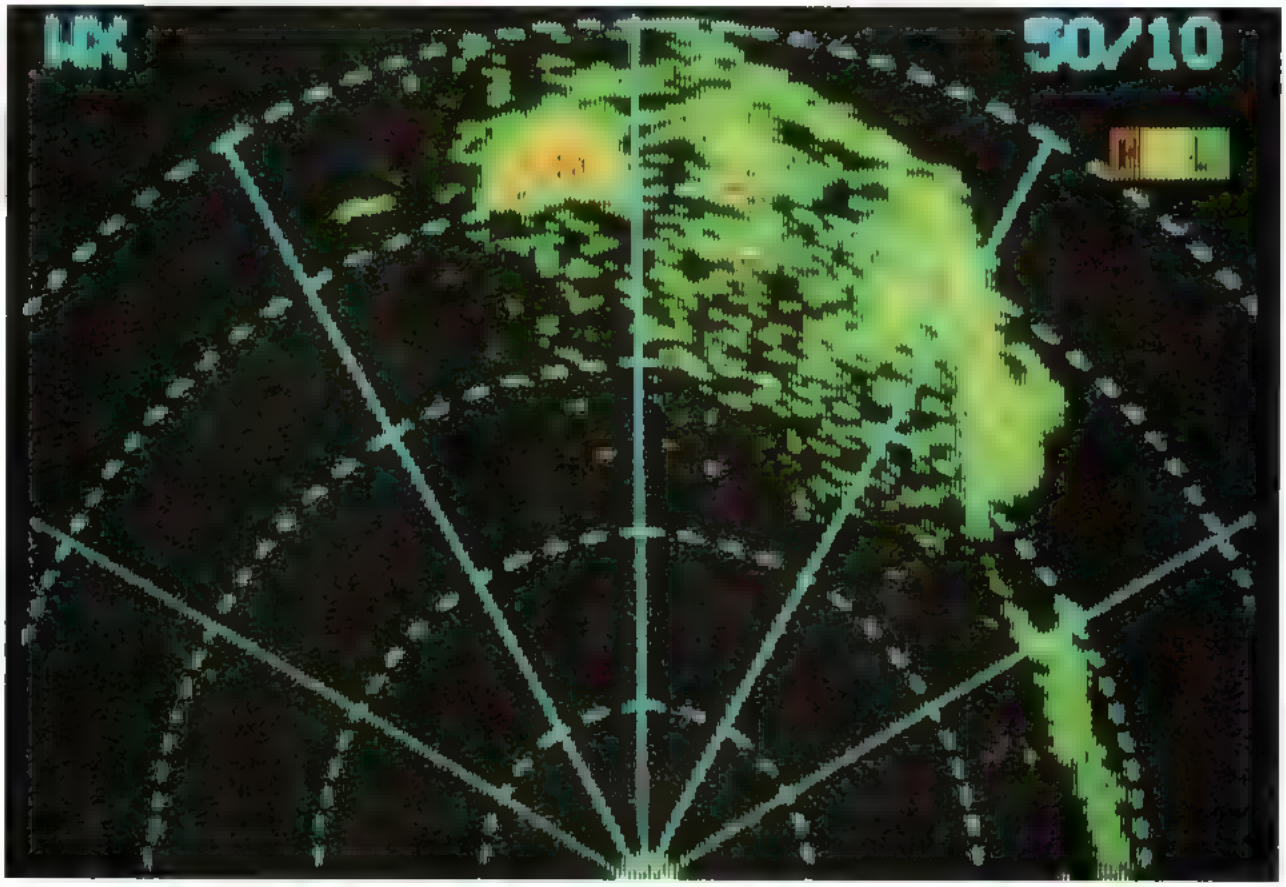


Figure A-8. Weather Radar With Multi-Color Display.

GLOSSARY

Advection fog - fog resulting from the transport of warm, humid air over a cold surface.

AFGWC - Air Force Global Weather Central.

Air mass - extensive body of air within which the conditions of temperature and moisture in a horizontal plane are essentially uniform.

Anticyclone - an area of high pressure which has a closed circulation that is anticyclonic, i.e., clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere.

Attenuation - the weakening of a radar signal caused primarily by the presence of precipitation, clouds, dust, and atmospheric gases.

Barometer - an instrument for measuring the pressure of the atmosphere; the two principal types are mercurial and aneroid

CAVOK - an acronym for Clear And Visibility OK. In a forecast this means no clouds below 5,000 feet, no Cb, visibility will be 10 km or more, and no precipitation, thunderstorm, or shallow fog is forecast.

Ceiling - the height above the earth's surface of the lowest layer of clouds or obscuring phenomena that is reported as broken, overcast, or totally obscured, and not classified as thin or partly obscured.

Circulation - continuous motion of the atmosphere relative to the earth's surface.

Clear Air Turbulence (CAT) - turbulence above 15,000 feet normally encountered in cloud-free air.

Clear ice - glossy, transparent ice formed by the relatively slow freezing of large supercooled water droplets.

Climate - the statistical collective of weather conditions of a point or area during a specified period of time.

Col - the neutral area between two highs and two lows.

Cold front - the leading edge of an advancing cold air mass.

Condensation - the physical process by which water vapor becomes liquid water.

Condensation trail (Contrail) - a cloud-like streamer frequently observed to form behind aircraft flying in clear, cold, humid air.

Contour - line on constant pressure upper air chart connecting points of equal altitude.

Convergence - air coming together from different directions. Areas of low-level convergent winds are regions favorable to the occurrence of clouds and precipitation.

Coriolis Force - a deflective force resulting from the earth's rotation; it acts to the right of wind direction in the Northern Hemisphere and to the left in the Southern Hemisphere.

Cyclone - an area of low pressure which has a closed circulation that is cyclonic, i.e., counterclockwise in the Northern Hemisphere, clockwise in the Southern Hemisphere.

D-Value - the difference between the actual height of any given pressure surface in the atmosphere and the height of that pressure surface in the standard atmosphere. D-Value = true altitude - pressure altitude.

Density altitude - altitude at which a given density is found in the standard atmosphere.

Dew point - temperature, at a given atmospheric pressure, to which air must be cooled to become saturated

Diurnal - daily, especially pertaining to a cycle completed within a 24-hour period and which recurs every 24 hours.

Divergence - condition of winds that exists within a given area such that there is a net horizontal flow of air outward from the region. Low-level divergent regions are areas unfavorable to the occurrence of clouds and precipitation.

Equatorial trough - the quasi-continuous belt of low pressure lying between the subtropical high-pressure belts of the Northern and Southern Hemispheres; sometimes referred to as the Intertropical Convergence Zone (ITCZ).

Equivalent chill temperature - the still air temperature corresponding to cooling effect produced by the observed combination of wind and air temperature.

Evaporation - process through which water vapor enters the atmosphere from liquid water.

Front - transition zone between two air masses that have different densities.

Frontal inversion - inversion resulting from movement of colder air under warm air or the movement of warm air over cold air.

Frontal wave - a cyclone which forms and moves along a front. The circulation about the cyclone center tends to produce a wave-like deformation of the front.

Frost - ice crystal deposits formed by sublimation on exposed surfaces when the temperature of the exposed surface is below freezing.

Funnel cloud - a violent tornado cloud extending downward from the parent cloud but not reaching the ground.

GRADU - term used in a forecast to indicate a change in weather expected to take place at an approximate constant rate throughout the period of the GRADU (gradual) times.

Ground fog - a fog that conceals less than 0.6 of the sky and does not extend to the base of any clouds

Gust front - the outward limit of gusty, low-level winds extending 10 to 15 miles from the base of a thunderstorm

Haze - a concentration of small dust or salt particles suspended in the air

High (anticyclone) - an area of high barometric pressure on a surface chart or a maximum of height (closed contours) on a constant pressure upper air chart.

Hurricane - a severe tropical cyclone in the North Atlantic Ocean, Caribbean Sea, Gulf of Mexico, and off the west coast of Mexico. Maximum sustained windspeed must be 64 knots or greater.

Ice fog - a type of fog composed of suspended particles of ice, usually occurring at temperatures of -20°F or colder.

Indefinite (ceiling designator) - identifies ceiling height as being vertical visibility into a surface-based obscuring phenomena. Regardless of method of determination, vertical visibility is classified as an indefinite ceiling.

Indicated altitude - altitude above mean sea level indicated on a pressure altimeter set at current local altimeter setting.

Insolation - incoming solar radiation falling upon the earth and its atmosphere

INTER - term used in a forecast to indicate weather conditions which will occur for less than 30 minutes (45 minutes for thunderstorms) of any hour, and less than one-half of the period for which the conditions are forecast.

Inversion - layer within the atmosphere characterized by an increase in temperature with altitude

Isobar - line connecting points of equal barometric pressure

Isotach - line drawn connecting points of equal windspeed

Katabatic wind - any wind blowing downslope.

Land breeze - a coastal breeze blowing from land to sea, caused by the temperature difference when the sea surface is warmer than the adjacent land.

Lapse rate - the rate of decrease of an atmospheric variable with height, most commonly refers to decrease of temperature with height.

Low (cyclone) - an area of low barometric pressure on a surface chart or a minimum of height (closed contours) on a constant pressure upper air chart.

Millibar (mb) - a pressure unit of 1000 dynes per square centimeter convenient for reporting atmospheric pressure

Monsoon - a seasonal shift in the surface wind.

Mountain breeze - the wind that descends a mountain at night.

NWS - National Weather Service.

Obscuration - denotes the sky is hidden by surface-based obscuring phenomena and the vertical visibility overhead is restricted.

Occlusion - the result of one frontal system overtaking a previously formed frontal system.

Orographic - of, pertaining to, or caused by mountains - as in orographic lift

Partial obscuration - a designation of sky cover when part of the sky is hidden by surface-based obscuring phenomena

PMSV - Pilot to Metro Service

Polar front - the zone which separates the polar and tropical air masses.

Precipitation - liquid or solid moisture that falls from the atmosphere in the form of rain, drizzle, ice pellets, snow, or combinations of them.

Pressure altitude - altitude indicated when altimeter is set to 29.92 inches; altimeter indicates height above the standard datum plan.

Pressure gradient - rate of horizontal pressure change.

Prevailing visibility - greatest horizontal visibility observed throughout at least half the horizon circle.

QFE (altimeter setting) - actual surface pressure. Altimeter indicates zero feet regardless of field elevation.

QNE (altimeter setting) - 29.92 inches, results in altimeter indicating height above standard datum plane or pressure altitude

QNH (altimeter setting) - altimeter setting which results in altimeter indicating height above mean sea level.

Radiation fog - fog produced over land when radiational cooling reduces the air temperature near the ground to or below its dew point. Usually occurs on clear nights with light winds.

Radiation inversion - inversion near surface of land caused when ground loses heat rapidly through terrestrial radiation, cooling the air next to it.

RAPID - term used in a forecast to indicate a fast change in the weather is expected to take place over a period of less than half an hour, i.e., "RAPID 23" means the change will occur about 2300Z.

Ridge - an elongated area of high pressure with the highest pressure along a line called a "ridge line."

Rime ice - rough, milky, opaque ice formed by the instantaneous freezing of small supercooled water droplets.

Runway Visual Range (RVR) - an instrumentally or visually-derived value that represents the horizontal distance an aircrew will see down the runway from the approach end.

St. Elmo's Fire - a luminous discharge of electricity from protruding objects on aircraft, especially canopies or windshields.

Saturation - condition that exists when air at a given temperature and pressure is holding the maximum possible water vapor content.

Sea breeze - a coastal local wind that blows from sea to land, caused by the temperature difference when the sea surface is colder than the adjacent land.

Slant visibility (approach visibility) - the distance from which the aircrew on final approach can see landing aids on the ground

Source region - the surface area over which an air mass originates.

Squall - a sudden increase in windspeed by at least 15 knots to a peak of 20 knots or more which lasts for at least one minute.

Squall-line - any nonfrontal line or narrow band of active thunderstorms

Stability - atmospheric resistance to vertical motion.

Stationary front - a front which is stationary or nearly so; conventionally, a front which is moving at a speed of less than 5 knots.

Stratosphere - the atmospheric layer above the tropopause, having an average altitude of base and top of 7 and 22 miles respectively.

Sublimation - changing of ice directly to water vapor or water vapor to ice, by-passing the liquid state in each process.

Subsidence - widespread sinking of air in the atmosphere.

Supercooled water - liquid water at subfreezing temperatures.

Temperature - the degree of "hotness" or "coldness" of a substance.

Terrestrial radiation - heat radiated from the earth by outgoing radiation.

Thermal current - a relatively small-scale convective current rising from the ground; it is produced when the air is heated locally by the earth's surface.

Thin (as in thin cloud deck) - designated by a minus sign, "-," prefixed to SCT, BKN, or OVC to indicate that one-half or more of the cumulative sky cover is transparent.

Thunderstorm - a local storm produced by a cumulonimbus (Cb) cloud always accompanied by lightning and thunder, and usually found with strong gusts of wind, heavy rain, severe icing and turbulence, and sometimes hail.

Tornado - a violent, rotating column of air extending from a cumulonimbus cloud and touching the ground. It starts out as a funnel cloud and is often accompanied by a loud roaring noise.

Tropics - the area of the earth which lies between the Tropic of Cancer (23½°N latitude) and the Tropic of Capricorn (23½°S latitude)

Tropical cyclone - a general term for any low that originates over tropical oceans.

Tropical depression - a tropical cyclone with maximum sustained winds of 33 knots or less.

Tropical storm - a tropical cyclone with maximum sustained winds between 34 to 63 knots

Tropopause - at top of troposphere, marking the boundary between the troposphere and stratosphere.

Troposphere - layer of atmosphere from surface to an average of about 7 miles.

Trough - an elongated area of low pressure along a line called a "trough line."

True altitude - actual altitude above mean sea level.

Turbulence - a condition of the atmosphere in which air currents vary greatly over short distances

Typhoon - a severe tropical cyclone in the western Pacific; maximum sustained windspeed must be 64 knots or greater.

Valley wind - warm air near the ground which rises out of a valley up a mountain slope during daytime.

Visibility - the greatest horizontal distance at which selected objects can be seen and identified

Warm front - the leading edge of an advancing warm air mass

Waterspout - a tornado over water.

Weather Flimsie - local weather briefing form used in lieu of DD Form 175-1. Most often used when several aircraft will be departing during the same time frame

Wind - air in motion relative to the surface of the earth; generally used to denote horizontal movement.

Wind shear - a change in windspeed and/or direction, resulting in a tearing or shearing action.

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